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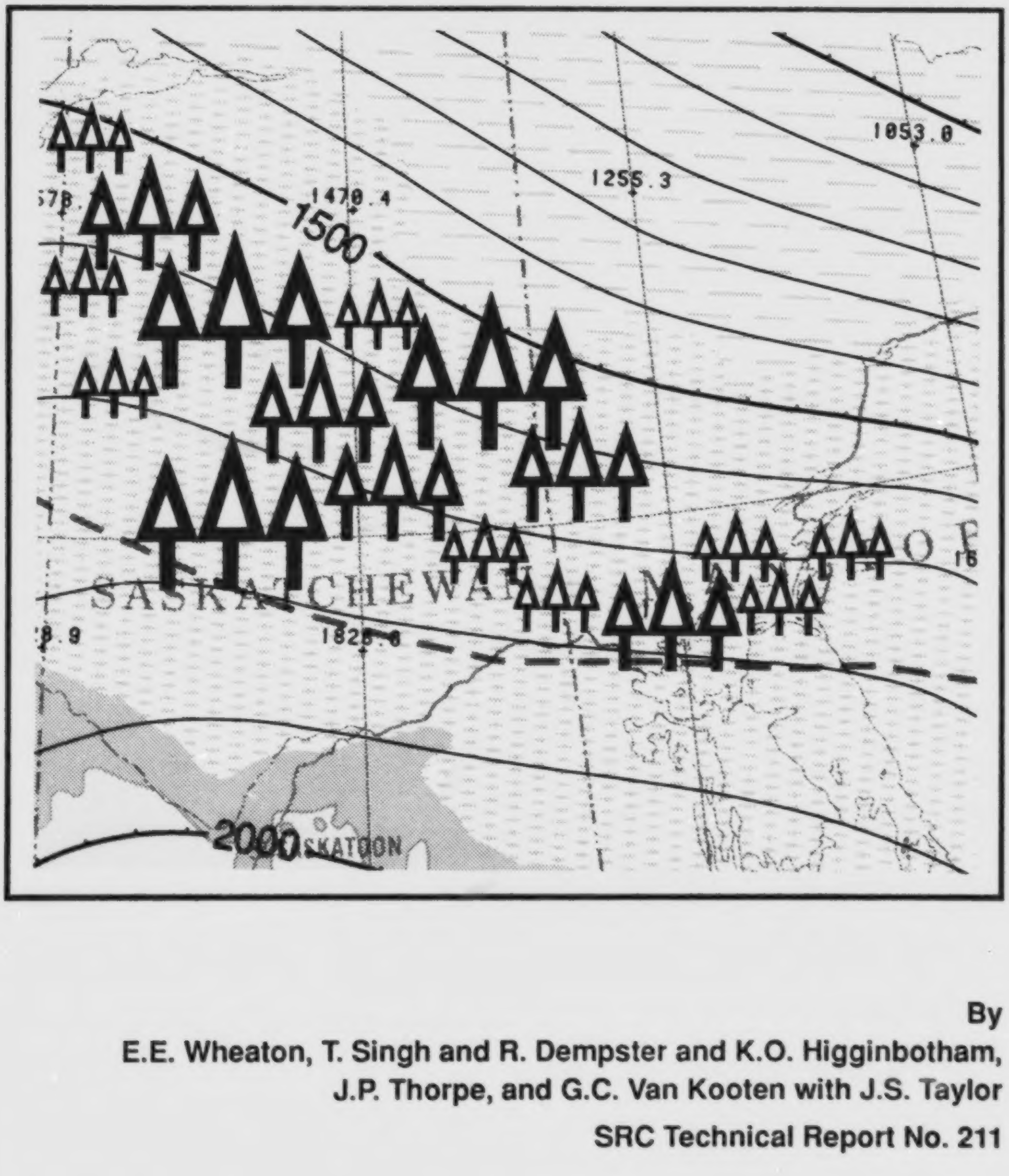
An Exploration and Assessment of the Implications of Climatic Change for the Boreal Forest and Forestry Economics of the Prairie Provinces and Northwest Territories:

Phase One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By
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J.P. Thorpe, and G.C. Van Kooten with J.S. Taylor

SRC Technical Report No. 211

SRC Publication No. E-906-36-B-87
November, 1987

AN EXPLORATION AND ASSESSMENT OF THE IMPLICATIONS OF CLIMATIC CHANGE FOR THE BOREAL FOREST AND FORESTRY ECONOMICS OF THE PRAIRIE PROVINCES AND NORTHWEST TERRITORIES:

PHASE ONE

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SRC Technical Report No. 211

Under contract with the Atmospheric Environment Service,
Environment Canada
DSS Contract No. 02SE.KM111-6-6330

SRC Publication No. E-906-36-B-87 November, 1987

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EXECUTIVE SUMMARY

INTRODUCTION

The report presents Phase I results of an exploratory study under a contract with the Canadian Climate Centre to assess the implications of CO_2-induced climatic change on the boreal forests in the Prairie Provinces and the Northwest Territories. The study area forms part of an extensive forestry belt extending from the eastern coast to Alaska which constitutes 82% of the forest land area in Canada. In addition to a significant contribution to the Canadian economy, the boreal forests provide irreplaceable habitat for wildlife, and perform valuable nonmarket functions such as watershed conservation and recreation.

The objectives of this study are:

1) To review and assess the current state of knowledge regarding CO_2-induced climatic change impacts on tree growth and physiology (including the direct effects of elevated CO_2), forest zonation, forest fires, insects and diseases, forestry management, forestry economics and policies;

2) To search for appropriate methodologies for assessing climatic change impacts on the topics listed in point one;

3) To develop a framework to assess the models for use in the climatic change-forestry-economics system and to develop a systems analysis design that can demonstrate and evaluate the linkages and feedbacks among models and modellers;

4) To evaluate, select and design climatic change scenarios for use in this study;

5) To undertake preliminary climatic change impact assessments quantitatively where possible, and qualitatively if this is not possible

at this time;

6) To determine recommendations for further study.

The climatic change of particular concern is that based on the well-documented rise in atmospheric carbon dioxide (CO_2) concentrations. The climatic change scenarios used to explore the CO_2-induced climatic change and its effects are hybrid types developed by applying General Circulation Model (GCM) based adjustments to historical climatic data (1951 to 1980 normals). The GCM adjustments for a 2 x CO_2 climate are those based on the Goddard Institute for Space Studies (GISS) and Geophysical Fluid Dynamics Laboratory (GFDL) GCM outputs for gridpoints within and around the study area (Street, pers. comm.).

RESULTS AND RECOMMENDATIONS

A summary of the results and recommendations pertinent to the climatic change effects on the previously mentioned topics is provided as follows:

Tree Physiology and Forest Ecology (Including the Direct CO_2 Effect)

1) Little is known about the basic physiological and growth responses of the boreal tree species in relation to limiting environmental factors such as CO_2, air and soil temperature, soil moisture, relative humidity, and soil nutrients. Basic and controlled environment studies need to be carried out for all the commercially important forest tree species.

2) Studies with lodgepole pine, white spruce and trembling aspen suggest a significant "fertilizer effect" of enhanced CO_2 on biomass production, height growth, leaf area production and branching in the

seedling stage. Virtually no information on direct effects of CO_2 enrichment on boreal tree species beyond the seedling stage is available. Modelling efforts are needed to simulate growth and physiology beyond the seedling stage to identify critical areas where future research should be undertaken.

The direct effects of CO_2-induced climatic warming on grasses and shrubs should also be studied because their likely increase in population and composition after harvesting and fires would have impacts on the success and failure of stand regeneration and establishment.

3) Data and modelling of ecosystem processes in the boreal forests are limited. Experimentation and modelling efforts need to be initiated to bring together information on ecosystem processes, including nutrient cycling, hydrology, and natural succession.

A number of problems need to be addressed for successful modelling of ecosystem processes. These include an assessment of evapotranspiration, genetic variability, potential ability of the forest tree species for acclimation, and the implications and magnitude of possible effects of improved water use efficiency.

4) Forest zone models should be developed for studying the projected changes and rates of changes of vegetation boundaries due to climatic change. Available climatic and forestry data from a large number of locations within each vegetation zone need to be accessed and utilized for better formulation and resolution of such models and revised boundaries.

Two types of models were used in this study for a preliminary assessment of climatic change impacts on boreal zonation, one based on growing degree-days and the other based on growing season temperatures and annual precipitation. The growing degree-day method shows that the forest-grassland interface and the predominantly forested area in the Prairie Provinces could gradually shift about 250 to 900 km north of their present locations (Table 1).

The other model was developed specifically for use in this study. When this vegetation zone model is used to assign present vegetation zones, it appears to perform correctly. With the GFDL climatic change scenario, the preliminary results indicate that the aspen parkland zone would extend into the western part of the study area and boreal-temperate forest would extend into the eastern part of the study area (Table 2). Refinement of this model based on more climate data is recommended.

Forest Productivity

1) Records of forest productivity obtained from growth layer analysis should be analyzed and related to climatic variation over time. Such information for commercial species in Canada is lacking, particularly for productive forest areas. A cost and time effective method for obtaining useful relationships would be to relate short-term historic climatic data with various measures of tree and stand productivity in different geographic locations having close proximity to existing climatic stations.

2) The effects of climatic change need to be studied in relation to tree quality as well as wood quality and density because of the relationship between rate of growth and wood density. As warming trends have occurred in the recent past, the dendroclimatological approach may prove useful in such studies.

Table 1. Shift (km) in the Northern and Southern Boundaries of the Boreal Forest (delimited by the 600 and 1300 growing degree-day isolines) as Implied by the GISS- and GFDL-based Climatic Change Scenarios.

Forest Boundary	Climatic Change Scenario	
	GISS	GFDL
Northern	80 to 720	100 to 730
Southern	470 to 920	250 to 900

Table 2. Change in Vegetation Zonation as Implied by the GFDL-based Climatic Change Scenario (with precipitation increases).

Gridpoint Location (latitude, longitude)	Present Zonation	GFDL1 Zonation
64.4° N, 120° W	subarctic	aspen parkland
59.9° N, 120° W	boreal	aspen parkland
55.5° N, 105° W	boreal	boreal-temperate
51.1° N, 112.5° W	grassland	grassland

3) Forested areas having climates similar to the climatic change scenarios should be examined as these could provide an indication of tree species and forest management suited to the expected change.

4) Forest growth and production models that use climatic data should be developed by modifying existing models to suit this study area and the study objectives. Model results should be tested against actual conditions. Biomass productivity should be calculated for both historical and climatic change scenarios to estimate potential changes. This would be useful information in view of the major shifts in vegetation boundaries projected for the study area.

Many models for forest growth and production were reviewed. These ranged from highly empirical types to highly mechanistic models, and included Lieth's Miami model, Paterson's CVP, Turc and Lecerf's Index, JABOWA, SUCSIM, FORCYTE and models of photosynthesis. These models were assessed based on aspects such as input requirements, parameters, output, theory and structure, verification, and documentation. None was found to be completely suitable for the purposes of this study.

A preliminary model relating forest productivity to climate was developed for this study. Multiple linear regression analysis of mean annual increment (MAI) on potential evapotranspiration and an index of moisture for 21 forest sections in the study area was used to produce the relationship. It shows a good statistical relationship between forest productivity and climate ($R^2 = 0.75$). Even with the limited dataset, there is significant positive relationship of forest growth rate to both growing season temperatures and moisture availability. This emphasizes the desirability of expanding the analysis by using a much larger dataset. It also clearly indicates that moisture effects, and not just temperature effects, must clearly be considered in projecting the productivity of forests in this part of the boreal forest.

Changes in potential biomass productivity under the influence of four climatic change scenarios were assessed using a few points in each of the three main forest zones (forest-grassland, predominately forest and forest-tundra). Potential biomass productivity was estimated using the Turc and Lecerf index (1972). The climatic change scenarios used as inputs to this model were the GISS- and GFDL-based scenarios both with and without the precipitation increases. Preliminary results shown in Table 3 indicate that potential productivity could increase up to about 50% above the productivity estimates based on the standard period normal climatic data (1951 to 1980 means). The productivity increases are considerably less without the increases in precipitation projected by the GCMs (Global Circulation Models). Model results need to be tested against productivity data, such as mean annual increment or net primary productivity, to determine how well productivity is simulated.

5) Existing forestry yield tables for specific sites may need to be adjusted based on the results from the climate-productivity models. This will provide the yield information needed for the economic models in further studies.

Forest Fires

1) The increase in summer temperatures and length of the frost-free season due to climatic warming will affect the intensity and frequency of forest fires. Information about the frequency of extreme weather events conducive to fire is necessary to assess the impacts of

Table 3. Climatic Change Impacts in Relation to Normal Climatic Values[a].

	Location A (58° 00'N 110° 00'W)		Location B (54° 00'N 105° 00'W)		Location E (64° 24'N 120° 00'W)		Location F (55° 30'N 105°00'W)	
	Climatic Change Scenario							
	GISS1	GISS2[b]	GISS1	GISS2	GFDL1	GFDL2[b]	GFDL1	GFDL2
	$(2xCO_2TP)$[c]	$(2xCO_2T)$	$(2xCO_2TP)$[c]	$(2xCO_2T)$	$(2xCO_2TP)$[c]	$(2xCO_2T)$	$(2xCO_2TP)$[c]	$(2xCO_2T)$
GROWING DEGREE-DAYS (GDD)	+35%	+35%	+48%	+48%	+40%	+40%	+31%	+31%
PRECIPITATION EFFECTIVENESS INDEX (I)	+22%	-10%	+12%	-10%	-6%	-8%	+16%	-7%
DRYNESS FACTOR (Fs)	+21%	+4%	-12%	-21%	-28%	-28%	+19%	+4%
HELIOTHERMIC FACTOR (HT)	+44%	+44%	+33%	+33%	+44%	+44%	+26%	+26%
BIOMASS POTENTIAL (CA)	+58%	+17%	+19%	-2%	+22%	+13%	+39%	+5%

	Location C (58° 00'N 120° 00'W)		Location D (50° 00'N 100° 00'W)		Location G (59° 54'N 120° 00'W)		Location H (51° 06'N 112°30'W)	
	GISS1	GISS2	GISS1	GISS2	GFDL1	GFDL2	GFDL1	GFDL2
GROWING DEGREE-DAYS (GDD)	+39%	+39%	+38%	+38%	+34%	+34%	+13%	+13%
PRECIPITATION EFFECTIVENESS INDEX (I)	+19%	-8%	+3%	-11%	+6%	-9%	+17%	-8%
DRYNESS FACTOR (Fs)	-3%	-17%	+4%	-2%	+10%	-4%	+2%	-24%
HELIOTHERMIC FACTOR (HT)	+54%	+54%	+21%	+21%	+55%	+55%	+46%	+46%
BIOMASS POTENTIAL (CA)	+53%	+27%	+1%	-12%	+46%	+13%	+118%	+44%

[a] Values are the percentage increases or decreases in relation to the mean climatic values for the 1951 to 1980 standard period (HIST). Locations are shown in Figure 1.1 of the main report.

[b] Scenarios GISS2 and GFDL2 use normal precipitation means.

[c] T and P stand for temperature and precipitation.

climatic change and variation. This information was not available from the GCM experiments and therefore estimates of impacts are only qualitative. The Canadian Fire Danger Rating System should be used to investigate these effects when more suitable climatic information is available.

2) Fire management strategies based on fire hazard information should be developed for resource management and planning under the climatic change scenarios. Such strategies will enhance fire damage management potential under increased risk.

Forest Insects and Diseases

1) The climatic warming and changed patterns of precipitation would likely affect the activity, abundance and distribution of some insects and diseases. In general, the projected changes in climate can be expected to increase the activity of most insects and diseases common in the boreal forest. The anticipated change in their population and composition needs to be investigated to ensure timely action for maintaining the health and well-being of our forests.

2) The likely effects of the changes in insect and disease infestations on tree growth and yield under impending climatic change should be studied and determined to enable precise estimation and management of forest resources and future timber supplies.

Forest and Range Hydrology

1) Hydrology of forests and rangelands will be affected by climatic change. As temperature and precipitation are major factors in hydrology, their impacts under the enhanced CO_2 scenarios would need to

be studied for various components of the hydrologic cycle.

2) Changes in snow accumulation and melt patterns, regime, and winter temperatures will affect timber harvesting practices and logging systems operative in some areas. Such impacts need to be studied and included in future planning strategies.

Forest Management

1) The frequency and intensity of droughts in a changed climate would affect regeneration and establishment of seedlings in the harvested and fire burnt areas. These will affect tree growth, annual allowable cut, and forest zonation. Such problems may be studied on a short-term basis through simulation modelling and controlled environment studies; these also need to be addressed on a long-term basis by field research and experimentation.

2) Soil moisture status and nutrient potential of forest lands should be studied as an essential prerequisite for accurate prediction of forest responses under a warmer climate.

Forest Economics

1) Future research concerning the economics of climate change impacts on Canadian forestry should consider the likely changes in forest supplies from other regions of the world as these will also be affected by a warmer climate. This will require the use of an international, econometric trade model to identify the elasticities of supply and demand, and their impacts in other regions.

2) A dynamic model based on increased risks and uncertainties under the changed climate scenario needs to be developed; the Leslie equation

approach is recommended for handling the physical requirements of such modelling.

3) In addition to commercial timber economics, it is essential to assess the nonmarket benefits accruing from recreational, scenic and other roles of the boreal forest. Research needs to be undertaken to determine the impacts of long-term climatic change on nonmarket values.

4) The existence value of the western boreal forest may be greater than all other values. However, no theoretical or empirical study has addressed this topic so far. It is necessary to identify how the impending changes in forest vegetation and zonation will affect the various functions associated with the boreal forests (e.g. waste receptor, water storage). This will require precise identification and investigation of these roles by physical scientists.

Policy Implications

1) The projected climatic change will probably involve shifts in forestry and agricultural zones, and may have significant implications for Canada. The likely impacts on forestry include changes in forest productivity, species composition, forest fires, insect and disease infestations, timber harvesting and restocking, forest zonation and water supplies. As these are matters of importance and concern to the inhabitants of the Prairie Provinces and Canada, these need to be properly addressed in future research coupled with policy formulation and planning.

2) The forestry impacts resulting from future climatic change will have important effects on forest industries in general. In addition, any shift in the present forest quality, quantity and boundaries of the

forest management areas may have serious consequences and management implications for successful operation of the industry. A case study should be undertaken to assess any such long-term effects.

3) Policy decisions should be integrated into the impact studies, possibly by dynamic modelling (Figure 1). Policy scenarios could be tested in the systems approach discussed in Section 3.6 so that decisions can minimize the harmful impacts and accentuate the benefits of climatic change.

The Interdisciplinary Approach

The cooperative effort required for this study clearly indicates that it is important to have interdisciplinary dialogue among all concerned scientists for assessing the impacts of CO_2-induced climatic change.

A preliminary climatic change-forest-economics system was developed for this study to illustrate the main components, impacts and linkages as well as to provide a framework for systems analysis (Figure 1). In summary, the performance and sensitivity of various impact models should be examined and compared critically. The systems analysis should be extended much beyond this initial stage in order to improve and integrate the models.

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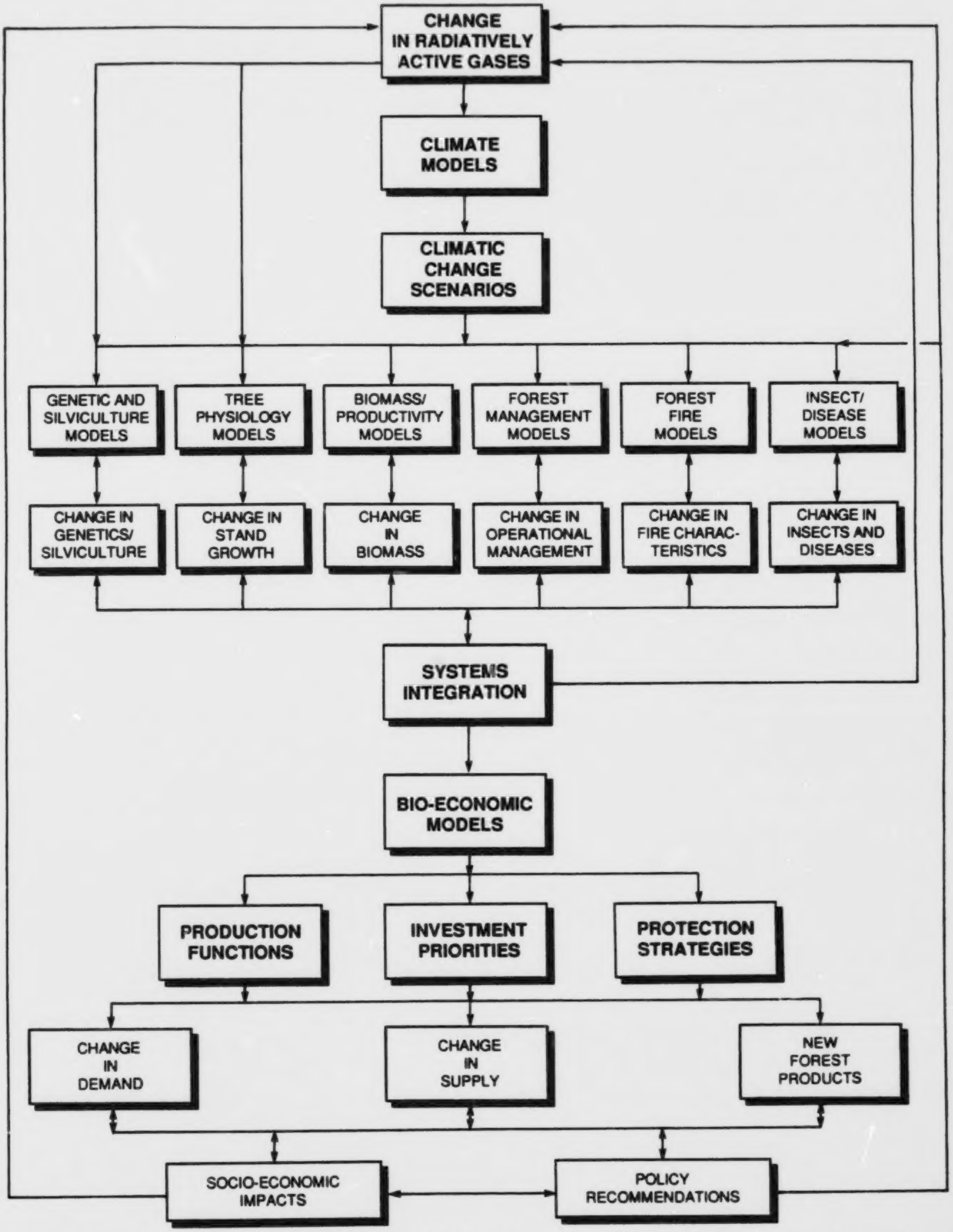
CHANGE IN RADIATIVELY ACTIVE GASES
CLIMATE MODELS
CLIMATIC CHANGE SCENARIOS
GENETIC AND SILVICULTURE MODELS
TREE PHYSIOLOGY MODELS
BIOMASS/ PRODUCTIVITY MODELS
FOREST MANAGEMENT MODELS
FOREST FIRE MODELS
INSECT/ DISEASE MODELS
CHANGE IN GENETICS/ SILVICULTURE
CHANGE IN STAND GROWTH
CHANGE IN BIOMASS
CHANGE IN OPERATIONAL MANAGEMENT
CHANGE IN FIRE CHARAC-TERISTICS
CHANGE IN INSECTS AND DISEASES
SYSTEMS INTEGRATION
BIO-ECONOMIC MODELS
PRODUCTION FUNCTIONS
INVESTMENT PRIORITIES
PROTECTION STRATEGIES
CHANGE IN DEMAND
CHANGE IN SUPPLY
NEW FOREST PRODUCTS
SOCIO-ECONOMIC IMPACTS
POLICY RECOMMENDATIONS

Figure 1. System Diagram Illustrating Climatic Change - Forest - Economics Interactions.

ACKNOWLEDGEMENTS

Funding for this work was provided by the Atmospheric Environment Service of Environment Canada. The authors thank R. Street and D. MacIver of the Atmospheric Environment Service for their useful comments. The authors acknowledge N.A. Stevens and C. Holmes for their contributions to this report. We thank G.D.V. Williams, retired agroclimatologist, for the model to calculate the potential biomass productivity, CA.

Many people at the Saskatchewan Research Council contributed to this report. Dr. J. Maybank, K. Lawrence and L. Baschak provided editorial comments. Technical help was provided by R. Begrand, R. Jahren, D. Richert, and R. Bouvier. B. McIntosh and C. Sardinha, Graphics Services, supplied most of the graphics. D. Diduck, K. Grayson, and L. Kunstmann, Departmental Services, performed most of the word processing. C. McKenzie made it possible to print the portions of the text containing equations. Many of the references were obtained by the Information Centre.

GLOSSARY AND ACRONYMS

Acclimation - process by which a plant adjusts its physiological responses as weather conditions (e.g. temperature) change.

Allocation - process by which carbohydrates produced by photosynthesis are apportioned to various plant functions (e.g. root growth, shoot growth, maintenance, etc.).

Aspen Parkland - transition zone in the prairie provinces between the boreal forest and the grassland, consisting of a mosaic of aspen groves and grassland patches.

Biomass - total mass (per unit area) of living matter in an ecosystem. Forest biomass may refer to mass of trees only.

Boreal Forest - vegetation zone extending across northern Canada and Eurasia, dominated by a few species of cold-tolerant conifers.

C_3 - carbon 3 photosynthesis.

C_4 - carbon 4 photosynthesis.

CA - climatic index of agricultural potential. CA is indicative of the potential for biomass productivity (Turc and Lecerf 1972).

CGE Models - computable general equilibrium models.

CLI - Canada Land Inventory.

Climate - the synthesis of the weather; the long-term manifestations of weather, often expressed by the statistical collective of its weather conditions during a specified interval of time (usually decades).

Climatic Change - describes longer-term changes in values of specific climatic variables between averaging periods.

Climatic Variability - describes the observed year-to-year differences in values of specific climatic variables within an averaging period (typically 30 years).

Cold-Hardening - series of physiological changes in plant tissue which enable it to survive low temperature.

Control Variable - the decision variable.

Current Assets - assets which can be converted into cash within one year.

Current Liabilities - debts which are payable within one year.

Current Ratio - the ratio of current assets to current liabilities.

Debt Ratio - the ratio of total liabilities to total assets; it is a measure of the extent to which a company uses debt for financing.

Decomposition - breakdown of dead plant material in the soil.

Dormancy - state of reduced physiological activity during winter.

DP - dynamic programing.

DTOC - discrete time optimal control model.

Dynamic Optimization - maximizing or minimizing an objective function over time.

Econometric Model - a statistically estimated model whose relations are derived from economic theory.

Economic Benefit - an economic surplus over and above cost accruing to an economic agent.

Ecosystem - system made up of atmosphere, soil, and living organisms, and the interactions among them.

FEPA - forest economics and policy analysis project.

Forest Fire Danger - expresses an assessment of both fixed and variable factors of the fire environment which determine the ease of ignition, rate of spread, difficulty of control and fire impact (Canadian Committee on Forest Fire Management).

Forest-Tundra - northern-most part of subarctic zone, where trees are confined to valleys and tundra occurs on ridges.

Fs - dryness factor.

GCM - general circulation model.

GDD - growing degree-days.

GFDL - Geophysical Fluid Dynamics Laboratory.

GISS - Goddard Institute for Space Studies.

Grassland - vegetation zone dominated by grasses, generally occurring in climates too dry for tree growth.

Growing Degree-Day - a measure of the departure of the mean daily temperature from a base temperature (typically 5°C): one degree-day for each degree of departure above this standard during one day.

Hardwoods - trees from the deciduous species.

HT - heliothermic index.

I - precipitation effectiveness index.

IM - index of moisture availability.

I-O - input-output.

IIASA - International Institute for Applied Systems Analysis.

Immature Wood - trees that have grown past the regeneration stage (greater than 1 m in height) but are not developed sufficiently for harvest.

Indirect Benefit - a net benefit (or cost) to society, which is captured by some economic agent, occurring in a market that is only indirectly affected by a policy action.

Indirect Effect - sometimes referred to as a secondary impact or impact, this is simply an income transfer from one region to another, or from one sector of the economy to another.

Input-Output (I-O) Model - fixed-coefficients relationships describing the current state of sales and purchases among all economic activities.

Insolvent - a firm's value of assets is too low relative to its liabilities.

Instar - a stage in the life of an arthropod (as an insect) between two successive molts.

Km - values of radiation at substrate level at one-half Vmax.

Lichen Woodland - vegetation in subarctic zone, consisting of widely spaced trees with lichens covering ground between them.

Liquidity - the ease with which assets can be converted into cash.

LP - linear programming.

MAI - mean annual increment.

Mature Wood - forest stands at or near rotation age.

Mean Annual Increment - rate at which wood volume is produced, per unit area per year, averaged over the length of a rotation.

Mesic Sites - sites in which the soil is neither excessively dry nor excessively wet.

NA-TAMM - North American timber assessment market model.

Net Primary Productivity - annual rate of production of new plant material in an ecosystem.

Nonmarket Amenity - a function or service provided by a resource which cannot easily be valued because it is not traded in the market place, although it does have value.

NPP - net primary productivity.

Nutrients - elements such as nitrogen, phosphorus, potassium, etc., required by plants and obtained from the soil.

Opportunity Cost - the foregone earnings of employing a resource as opposed to using it in its (next) best alternative.

Optimal Time Path - the "best" choice of the control variable in each period of time or the value of the state variable in each period of time when the optimal values of the control variables are chosen in each period.

Overmature Wood - forest stands past rotation age.

PE - potential evapotranspiration.

PhAR - photosynthetically active radiation.

Phenology - sequence and timing of plant developmental stages through the growing season.

Photosynthesis - process by which plants use carbon dioxide, water, and solar energy to produce high-energy carbohydrates. Gross photosynthesis is the total amount of photosynthesis, while net photosynthesis is gross photosynthesis minus respiration.

Physiology - study of functions and processes within living organisms.

PPT - annual precipitation.

Productive Forest - a forest capable of producing merchantable timber within a reasonable period of time.

Productivity - rate at which new biomass is produced, per unit area per year. "Net primary productivity" is a more specific term, referring to production of plant biomass only.

Regeneration - renewal of a forest crop by natural or artificial means.

Reserved Land - forest land that by law is not available for the harvest of forest crops.

Respiration - process by which plants (and other organisms) consume carbohydrates (and other compounds) to obtain energy. Maintenance respiration provides energy needed for maintenance of existing tissues, while growth respiration provides energy for growth of new tissues.

Rotation - in forestry, the period of time over which a stand of trees is grown before harvest.

SIC - Standard Industrial Classification.

Site Index - a measure of the rate of height growth in trees, expressed as the height that would be attained at some index age (e.g. 50 years).

SNECS - simulator of northern ecosystems.

Softwoods - trees from the coniferous species.

Standard Industrial Classification (SIC) - an international system for classifying establishments into industries for statistical purposes.

State Variable - an observed variable which may or may not be influenced by policy choices.

Stomata - pores in the surface of leaf which open and close, and through which gases (e.g. carbon dioxide, oxygen, water vapour) pass into and out of the leaf.

Stomatal Conductance - a measure of the rate at which gases move through the stomata.

Subarctic - the zone of transition between the boreal forest and the arctic tundra.

TAMM - timber assessment market model.

Temperate Deciduous Forest - forest dominated by broad-leaved deciduous trees, occurring in warmer climates than the boreal forest (e.g. eastern United States).

Timberline - the limit of occurrence of trees at high altitudes or high latitudes.

Transpiration - process of water flow through plants, from uptake of soil water by roots to evaporation of water from leaves.

Tree Rings - layers of new wood laid down annually around the stems of trees.

TRIM - tree ring increment measuring system.

Tundra - vegetation dominated by low plants (mosses, lichens, dwarf shrubs, grasses, sedges), occurring in climates too cold for tree growth.

Value Added - the increase in a product's value at a particular stage of production; it is equal to salaries and wages plus depreciation plus net operating surplus at that stage.

Vmax - maximum photosynthetic rate.

Weather - the state of the atmosphere, mainly with respect to its effects upon life and human activities. As distinguished from climate, weather consists of the short-term (minutes to months) variations of the atmosphere.

WUE - water use efficiency.

Yield Table - table showing the yield of wood from a stand of trees at a series of ages.

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1 INTRODUCTION

The boreal forest is of considerable importance to Canadian society, economy and to several aspects of the environment. There is also inherent value solely in its existence. The forest under consideration in this study is that portion of the northern or boreal forest in the Prairie Provinces and Northwest Territories (Figure 1.1). The forest provides irreplaceable habitat for wildlife, other plants and fish. Furthermore, the forest acts to regulate water flows and prevent soil erosion. Thus recreation and tourism based on these aspects of the environment are made possible.

The significance of forestry to the Canadian economy should be emphasized; in 1984, forestry products accounted for 14.0% of all Canadian exports. The contribution of the Prairie Provinces to forest production can be determined by examining statistics for the study area relative to that for Canada as a whole (Table 1.1). The study area accounts for 5.1% of all employment, value-added and value of shipments in forestry; and it accounts for 4.5% of total forest product exports.

Nonetheless, the region constitutes 36.7% of the total available productive forest land area in Canada, and 24.0% of the unproductive forest land area. In addition, the study area's forest accounts for over 13% of the gross merchantable timber volume available in Canada. Thus, although these forests do not contain as much commercial timber, by volume, as some of the other areas in Canada, particularly the coastal region of British Columbia, the study area forests are also under-exploited at the present time. The main reason they are under-exploited has to do with accessibility and distance to market, although these problems are decreasing as remote regions are opened up for other

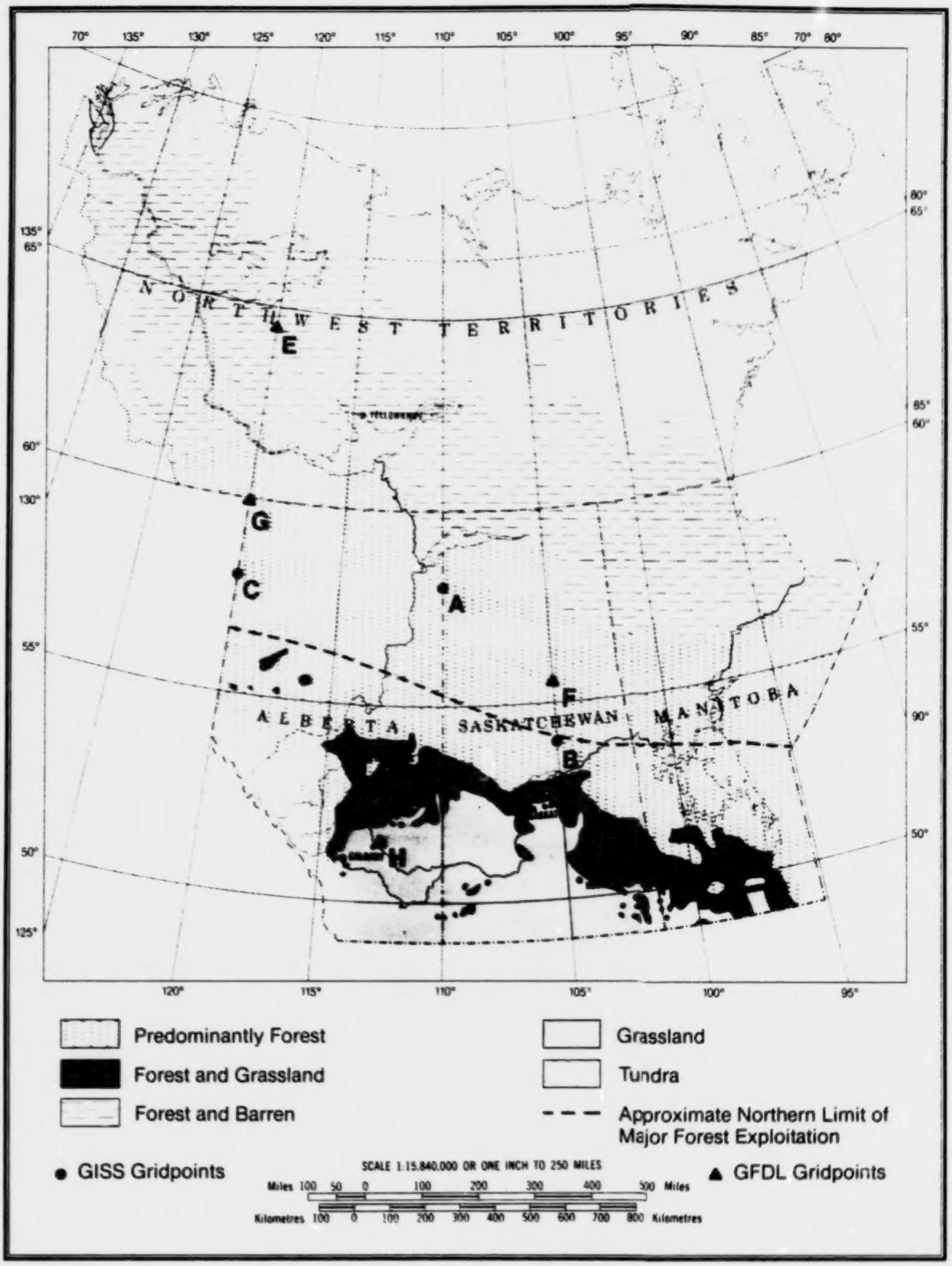
NORTHWEST TERRITORIES
ALBERTA
SASKATCHEWAN
MANITOBA
A
B
C
E
F
G
H
70°
135°
130°
125°
120°
115°
110°
105°
100°
95°
90°
85°
80°
65°
60°
55°
50°
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
● GISS Gridpoints
▲ GFDL Gridpoints
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure 1.1 Map of the Study Area -- the Boreal Forest Region of Western Canada.
Source: Rowe (1972) for vegetation zonation and northern limit of major exploitation.

Table 1.1 Forestry Statistical Summary for the Study Region Relative to Canada as a Whole.

	Canada	Alberta	Saskatchewan	Manitoba	Prairies
FORESTED AREA (1981)			(1,000 km^2)		
Productive	2,642	234	111	624	969
Unproductive	1,723	115	89	209	413
INVENTORY OF GROSS MERCHANTABLE WOOD VOLUME (1981)			(1,000,000 m^3)		
Softwoods	15,570	781	293	439	1,513
Hardwoods	4,074	657	191	196	1,044
Total	19,644	1,438	484	635	2,557
EMPLOYMENT (1983)					
Logging Industry	45,943	746	560	446	1,752
Wood Industries	101,965	5,418	X	2,010	7,428
Paper & Allied Industries	114,308	2,239	X	1,859	4,198
VALUE ADDED (1983)			($1,000,000)		
Logging Industry	2,158	33	33	14	80
Wood Industries	3,993	235	X	59	294
Paper & Allied Industries	5,940	165	X	79	244
VALUE OF SHIPMENTS OF GOODS (1984)					
Logging Industry	5,364	96	72	56	227
Wood Industries	9,973	539	110	135	784
Paper & Allied Industries	17,472	452	X	218	670
EXPORTS (1984)	15,730	415	146	145	701

X indicates that the information is confidential under the Statistics Act.

Note: The statistics for the Northwest Territories alone are not available as they are combined with British Columbia's statistics.

Source: Canadian Forestry Service (1986).

uses and cheaper modes of transport become available.

What is the connection to climate? The structure and function of a forest ecosystem is more clearly dependent on climate than many other ecosystems (Havas 1971). The climatic control of the distribution of the boreal zone, especially its northern limit, is well documented (Peterson et al. 1983). Many characteristics of the forest, including tree physiology and productivity, vegetation zones, fires, insects and diseases are inextricably linked to climate.

Climate has changed in the past and will likely continue to change in the future. The climatic change of particular concern currently is that based on the well-documented rise in atmospheric carbon dioxide (CO_2) concentrations. Atmospheric levels of CO_2 have increased from about 283 ppm in 1860 to 340 ppm in 1983 (Gates 1983; Plass 1959). Changes are also being observed in other atmospheric constituents that affect the earth-atmosphere heat budget. Amounts of other radiatively active gases, such as the chlorofluorocarbons, methane, nitrous oxide and other trace gases, are also increasing. If present trends continue, the combined concentrations of atmospheric CO_2 and the other "greenhouse gases" would be radiatively equivalent to a doubling of CO_2, as compared to preindustrial levels, as early as the 2030's (A Villach, Austria Conference Statement in Environment Canada 1986).

A recent paper (Jones et al. 1986) provides observational evidence of worldwide warming over the past 100 years; this change is of the same direction and correct magnitude of the change predicted by General Circulation Model (GCM) simulations. GCM simulations of a climate with increased CO_2 levels clearly show increased temperatures, especially at higher latitudes. Therefore, as doubling of atmospheric CO_2

concentrations is likely to cause global warming, alter atmospheric pressure and precipitation patterns and amounts (Manabe and Wetherald 1975). The temperature effect is expected to be most significant in northern latitudes where long periods of snow cover increase the annual albedo of the land surface. Any reduction in the period of snow cover yields an amplified temperature increase (Pollard 1985).

Another question is whether or not regional or even local trends are following the same patterns and are of the same magnitude as global or even northern hemispheric trends. Singh and Powell (1986) examined the climatic variation and trends of the boreal forest of the Prairie Provinces and Northwest Territories and found that the area exhibited significant ($P<0.05$) warming trends during the 1872 to 1981 period. Shewchuk (1984) noted an apparent trend toward increasing temperatures at Saskatoon, Saskatchewan, in the past two decades, particularly in winter. Therefore, the regional trends appear to be suggesting increasing temperatures for the study area.

What are the implications of climatic warming for the boreal forest? Climatic factors related to temperature exert more obvious controls over primary productivity in boreal forest ecosystems than those related to precipitation and its related variables (Peterson et al. 1983; Kauppi and Posch 1985). The effects of climatic change may be quite pronounced because of the combination of the forest's sensitivity to climate, especially temperature, and the fact that the greatest temperature increases are expected for the high latitudes, which is where the boreal forest is located.

Also, unlike the effects on other sectors such as transportation, recreation, energy, etc., the increase of atmospheric CO_2 has a doublefaceted effect on vegetation. In addition to the climatic impact, there is the physiological response of the plant. CO_2 is an essential requirement for plant growth and, within limits, increases plant growth and primary productivity (e.g. Dahlman 1985). Water use efficiency for some plants also increases with increasing CO_2 levels (e.g. Rogers et al. 1983). This latter effect is especially important in the southern boreal forest, for example, where moisture stress may be restrictive for growth. With climatic warming, moisture stress could also become more significant in the northern portion of the boreal forest.

Responses in the global boreal forest to climatic change are important to understand because of the vast extent of these forests, their economic importance, and the fact that CO_2-induced climatic change is predicted to be particularly pronounced at boreal latitudes. Because climate so strongly affects this vital renewable resource, its influence on the forest should be carefully studied especially in view of the implications of climatic warming.

1.1 Objectives

The implications of climatic warming on the boreal forest of the study area are considered by means of the following main topics: tree growth and physiology, direct effect of CO_2-enrichment, forest productivity, forest zonation, forest fires, insects and diseases, forest management, economics and policies. The search for the best and most appropriate methodology is a primary consideration. Therefore the objectives of this study are:

1) To review and assess the current state of knowledge regarding CO_2-induced climatic change impacts on each of the previously mentioned

main topics.

2) To search for appropriate methodologies for assessing climatic change impacts on these topics.

3) To develop a framework to assess the methods for use in the climatic change-forestry economics system. The framework includes a matrix of the models and the characteristics thought to be required for such a climate impact study. Then the most appropriate models for impact assessment can be selected.

4) To develop a systems analysis design that can demonstrate and evaluate the linkages and feedbacks among the models and modellers. Communication among the disciplines involved is necessary and is emphasized in order to develop this integrated interdisciplinary climate impact assessment. The most appropriate information to be provided to other disciplines is developed through close coordination with all members of the study team. The systems design is the outcome and epitome of this approach.

5) To evaluate, select and design climatic change scenarios for use in this study. The results of two GCMs are to be used in various combinations with historical climatic data.

6) To undertake preliminary climatic change impact assessments. Three main types of effects are explored through impacts experiments: i) effects on derived climatic parameters thought to be of importance to the boreal forest (e.g. growing degree-days, precipitation effectiveness, etc.), ii) effects on forest zonation and iii) effects on biomass potential and productivity.

7) Where experimentation is not possible because of lack of time or a model, for instance, suggestions of possible climatic change impacts

are made for several topics. For example, the impacts on the structure and function of the boreal forest ecosystem, and on fire, are evaluated qualitatively.

8) To draw initial conclusions and to determine recommendations for further study.

1.2 The Study Area-Boreal Forest Region of the Prairie Provinces and Northwest Territories

As discussed previously, the vegetation of the study area is very sensitive to climate. Climatic warming, due to the greenhouse effect, is thought to be more pronounced at high latitudes - the location of the study area. Therefore the effect of climatic change on the study area may be quite pronounced and should be carefully assessed.

An understanding of the physical, especially vegetative, and economic aspects of the study area is useful in the assessment of the impacts of climatic change on the forest and forestry economics. These attributes are discussed in the next two sections. The first section is a brief discussion of the vegetation of the area, with an emphasis on forest species and vegetative zonation. The importance of forestry to the Canadian economy and the size of the study area relative to the Canadian economy as a whole are the subjects of the second section. This section also gives emphasis to the structure and financial soundness of the industry.

1.2.1 Vegetation of the Study Area

The physical characteristics of the study area, such as physiography, climate and soils, are illustrated and described in several other references (e.g. Larson 1980). Therefore, only a brief description of the relevant aspects of the forest vegetation is provided in this section.

The boreal forest of the study area is not as diverse as tropical forests, or even eastern North American hardwood forests, but there are still substantial numbers of species present. The most important of these are: balsam fir, white birch, tamarack, white spruce, black spruce, jack pine, lodgepole pine, balsam poplar and trembling aspen. Appendix A lists other common names for these species as well as their scientific names. From a commercial point of view, white spruce, black spruce, trembling aspen and jack pine are the most important.

The influence of climate on the boreal forest is reflected in the zonation of forest types. Transition zones occur northward to the arctic tundra, and southward to the temperate grassland in the Prairie Provinces, and with the temperate deciduous forest in eastern North America. The region is usually subdivided by vegetation from south to north into three subregions (Maini 1968) as shown in Figure 1.1 and listed as follows:

1) forest-grassland transition: occupied primarily by trembling aspen, willows, and other shrubs and grasses;

2) predominantly forest: consisting mainly of white spruce, black spruce, balsam fir, jack pine, trembling aspen, and white birch;

3) forest-tundra transition: consisting mostly of white and black spruces, dwarf birch, black crowberry and lichens and mosses.

Other zonation schemes have been used. A discussion of the zonation of the boreal forest is in Section 2.6.

1.2.2 Economic Structure of the Study Area

The forest industry is discussed in some detail here. The objective is to provide a description of the forest and related industries, with particular reference to the study region. This section forms the basis for assessment of changes in economic structure to be undertaken in future studies.

1.2.2.1 Classification of Forest Activity: The Standard Industrial Classification

For statistical purposes, the Standard Industrial Classification (SIC) is used to arrange producing units into industries (Needham 1969: 22-28). This section uses the 1980 revised SIC to classify forest industries as indicated in Figure 1.2. Unfortunately, it is sometimes necessary to change the standard industrial classification as the economic world changes, giving rise to problems in class reporting. For example, in 1980, the Major Group Logging (SIC 03) was changed to Major Group 04.

The Standard Industrial Classification groups establishments according to their activity structure, with the highest level called the Division. There are ten alphabetical Divisions with Logging and Forestry Services under Division C. Each Division is made up of Major Groups which represent an aggregation of Industry Groups. The Major Group is assigned a two-digit number; for example, under Division C, Logging is Major Group 04 and Forestry Services Industry is Major Group 05. The other Division that is relevant to this section is Division E, Manufacturing. Manufacturing includes two Major Groups or two-digit industries that are relevant to the current study, namely, Wood Industries (25) and Paper and Allied Industries (27).

STANDARD INDUSTRIAL CLASSIFICATION

- FOREST INDUSTRIES
  - LOGGING 04
  - FORESTRY SERVICES 05
  - WOOD INDUSTRIES 25
    - 251 Sawmills, planing mills, and shingle mills
      - 2511 Shingle and shake mills
      - 2512 Sawmills and planing mills
    - 252 Veneer and plywood mills
      - 2521 Hardwood veneer and plywood mills
      - 2522 Softwood veneer and plywood mills
    - 254 Sashes, doors, and other millwork
      - 2541 Prefabricated wooden buildings
      - 2542 Wooden kitchen cabinets and bathroom vanities
      - 2543 Wooden doors and windows
      - 2549 Other millwork
    - 256 Wooden boxes and pallets
    - 258 Coffins and caskets
    - 259 Other wood industries
      - 2591 Wood preservation
      - 2592 Particle board
      - 2593 Waferboard
      - 2599 Other wood industries n.e.c.
  - PAPER AND ALLIED INDUSTRIES 27
    - 271 Pulp and Paper
      - 2711 Pulp
      - 2712 Newsprint
      - 2713 Paperboard
      - 2714 Building Board
      - 2719 Other paper
    - 272 Asphalt roofing
    - 273 Paper boxes and bags
      - 2731 Folding carton and set-up boxes
      - 2732 Corrugated boxes
      - 2733 Paper bags
    - 279 Other converted paper products
      - 2791 Coated and treated papers
      - 2792 Stationery
      - 2793 Paper consumer products
      - 2799 Other converted papers

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986 p. 73.

Figure 1.2 Standard Industrial Classification Canada 1980

Each Major group is then divided further into three-digit Industry Groups, with the Major Group code repeated at this level; for example, the three-digit industry 252 is Veneer and Plywood Mills, which is under Major Group 25. These Industry Groups are then subdivided into four-digit classes in which the Major Group and Industry Group codes are repeated; for example, the four-digit industry 2521 represents Hardwood, Veneer and Plywood Mills, which is the Industry Class under the three-digit Industry Group SIC 252.

1.2.2.2 Financial Condition

The financial condition of the forest industry is summarized using liquidity ratios in Table 1.2. The financial condition is the relationship between the industry's assets and the way in which they are financed. The liquidity ratios used in this table are quick, simple measures which are subject to imperfections, but they may suggest liquidity problems.

The current ratio compares the current assets to the current liabilities in ratio form, that is,

Current Ratio = current assets/current liabilities.

This ratio is useful in making comparisons between companies of different size. According to Mumey (1977:214), a current ratio of two or greater indicates adequate liquidity, while a current ratio of less than one may be an indicator of financial difficulty, although there are many exceptions.

The debt ratio in Table 1.2 measures the industry's potential for insolvency. An industry fails when it is in a state of insolvency, in other words, when asset value is low relative to liabilities. This

Table 1.2 Forest Industry Liquidity Ratios, 1981-1984.

	1981	1982	1983	1984
Forest Industry[a]				
Current Ratio	.9	.8	.9	.9
Debt Ratio	.7	.6	.6	.6
Sawmills and Planing Mills (251)				
Current Ratio	1.4	1.3	1.4	1.3
Debt Ratio	.7	.7	.7	.7
Veneer and Plywood (252)				
Current Ratio	1.6	2	1.9	1.4
Debt Ratio	.6	.6	.6	.7
Pulp and Paper Mills (271)				
Current Ratio	1.9	1.7	1.4	1.6
Debt Ratio	.6	.6	.6	.6

[a] These ratios are calculated for the Logging and Forestry Services Industry only, resulting in a current ratio of less than one.

Note: Numbers in brackets are the standard industrial classification.

Source: Corporation Financial Statistics
Catalog 61-207
Statistics Canada (Various dates)

ratio is calculated as:

Debt Ratio = total liabilities/total assets.

The debt ratio measures the extent to which a company uses debt. For manufacturing industries, 0.5 may be regarded as normal (Mumey 1977: 218). Ratios less than this could indicate inadequate use of debt. Ratios larger than 0.5 may indicate insolvency problems. The debt ratios calculated in this table are based on accounting values and do not take into consideration the market value of the firm's net worth. Further, the industry-wide debt ratio does not indicate whether individual firms may be having financial problems.

It would appear from Table 1.2 that forestry firms are in general financially sound, whether in the logging business or in secondary manufacturing.

1.2.2.3 Corporate Ownership

Of the 7,633 Forestry Industry establishments in Canada, 659 of them are located on the prairies. These include the establishments under SIC 04 and 05 which are the Logging Industry and Forestry Services Industry, respectively. The Logging Industry alone makes up 219 of these 659 establishments. In the Paper and Allied Industry (SIC 27), the prairies have 63 of the 672 establishments in Canada. There are also a number of Wood Industry establishments on the prairies. Alberta has 220 Wood Industry establishments, compared to 100 in Manitoba and 57 in Saskatchewan. Together the Prairie Provinces account for 377 of the 3,453 Wood Industry establishments in Canada.

Ownership of forest industry firms is primarily private although there is some public ownership; for example, Manitoba Forestry Resources

Ltd. is controlled by the Government of Manitoba. In addition, there is a substantial amount of foreign ownership; for example, the Simpson Timber Company of the U.S. controls many establishments in Alberta, Saskatchewan and Manitoba. However, it is important to note that the federal and provincial governments own over 90% of all forest lands (Table 1.7).

1.2.2.4 Employment in the Forest Industries

Employment by industry and province for the period 1980-1983 is listed in Table 1.3. Manitoba and Alberta employ an average of 5.1% of forestry workers in Canada and 3.7% of all Paper and Allied Industries workers. In the Wood Industry, the prairies employ 9.1% of all workers in Canada, and in the Logging Industry 4.3% of those employed in Canada are located on the prairies.

Employment in the Forestry Industry is summarized in Table 1.4 for the years 1980-1983. The number of establishments, employees, salaries and wages, and the total value added by industry class are provided. During 1980-1983, wages increased by an average of 7% annually in the Sawmill and Planing Industry, 14% in the Veneer and Plywood Industry, 10% in the Pulp and Paper Industry, and 23% in all Forest Industries. The total wage bill in all the Forest Industries increased by 53.4% over the period 1982-1983. The average annual wage rate in the Forest Industry for this period was $26,217.00. In 1983, the average yearly wage reached $36,943.00.

In Table 1.5, the number of establishments and employees, salaries, wages, and total value added are listed by province and industry for 1983. For all Forest Industries, the prairies have 8.6% of the

Table 1.3 Employment by Forest Section and Province, 1980-1983.

Year	Manitoba	Saskatchewan	Alberta	Canada
A. FOREST INDUSTRIES				
1980	4928	X[a]	10038	301987
1981	5097	X	10384	291996
1982	4342	X	8828	254875
1983	4315	X	8403	262240
B. WOOD INDUSTRIES				
1980	1993	1596	6634	117307
1981	2158	1620	6904	112570
1982	1852	1343	5765	97050
1983	2010	X	5418	101965
C. PAPER AND ALLIED INDUSTRIES				
1980	2408	X	2384	130310
1981	2361	X	2499	131024
1982	2041	X	2210	117669
1983	1859	X	2239	114308
D. LOGGING				
1980	527	605	1020	54370
1981	578	599	981	48402
1982	449	575	853	40156
1983	446	560	746	45943

[a] X indicates that information is confidential under the Statistics Act.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986

Table 1.4 Forest Industries Summary, 1980-1983.

Year	Estimated No. Establishments	Estimated No. Employees	Salaries & Wages ($000 000)	Total Value Added ($000 000)
A. Sawmill & Planing Mill Industry (SIC 2512)				
1980	1317	66278	1379	2089
1981	1313	62774	1373	1827
1982	1230	53698	1286	1494
1983	1290	58135	1509	2463
B. Veneer & Plywood Industry (SIC 252)				
1980	84	12363	243	345
1981	77	11323	238	357
1982	82	10344	225	254
1983	82	9724	256	381
C. Pulp & Paper Industry (SIC 271)				
1980	144	86872	2050	5355
1981	144	87882	2310	5401
1982	142	83104	2442	4515
1983	137	79164	2528	4380
D. All Forest Industries				
1980	7368	301987	6180	12285
1981	7428	291996	6624	12295
1982	7100	254875	6315	10234
1983	7633	262216	9687	12091

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986

Table 1.5 Forest Industries - Selected Provinces by Sector, 1983.

	Estimated Number of Establishments	Estimated Number of Employees	Salaries & Wage ($000 000)	Total Value Added ($000 000)
A. FOREST INDUSTRIES				
Manitoba	167	4315	93	152
Saskatchewan	141	X[a]	65	X
Alberta	351	8403	222	433
Prairies	659	12718	380	585
Canada	7633	262216	6987	12091
B. LOGGING (SIC 04)				
Manitoba	38	446	11	14
Saskatchewan	79	560	15	33
Alberta	102	746	20	33
Prairies	219	1752	46	80
Canada	3508	45943	1219	2158
C. PAPER AND ALLIED INDUSTRIES (SIC 27)				
Manitoba	29	1859	46	79
Saskatchewan	5	X	20	X
Alberta	29	2239	70	165
Prairies	63	4098	136	244
Canada	672	114308	3341	5940
D. WOOD INDUSTRIES (SIC 25)				
Manitoba	100	2010	36	59
Saskatchewan	57	X	30	X
Alberta	220	5418	132	235
Prairies	377	7428	198	294
Canada	3453	101965	2427	3993
E. SAWMILL AND PLANING MILLS PRODUCTS INDUSTRY (SIC 2512)				
Manitoba	18	350	7	6
Saskatchewan	11	492	13	21
Alberta	51	2392	63	112
Prairies	80	3234	83	139
Canada	1290	58135	1509	2463

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[a] Confidential under the Statistics Act.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986

establishments in Canada. In 1983, 5.4% of the Forest Industry wages in Canada went to Manitoba, Saskatchewan and Alberta. The value added by salaries and wages for Manitoba and Alberta was 4.8%.

In the Logging Industry, 6.2% of the establishments are on the prairies, and 3.8% of wages in Canada went to prairie workers. Salaries and wages contributed 3.7% to total value added for the Logging Industry. Paper and Allied Industry workers on the prairies make up 9.3% of those employed in Canada and they receive 4% of total wages in Forest Industries. Manitoba and Alberta's value added from salaries and wages is 4.1% of the total value added. Eleven percent of all establishments in the Wood Industry are on the prairies and these receive 8.2% of the total Wood Industry wage in Canada. The total wages from Manitoba and Alberta contribute 4.1% to the Canadian total value added. Under the Major Group (SIC 25 or Wood Industries), 6.2% of the Sawmill and Planing Mills Products Industry (SIC 2512) establishments in Canada are located on the prairies. In 1983, these employees received 5.5% of the total wages in this industry and contributed 5.6% of the total value added.

The most current employment data for the forestry industry are found in Table 1.6. Forestry employment includes Forestry Services and the Logging Industry only. The prairies have 6.9% of the total forestry employment in Canada. The average wage for the forestry industry on the prairies is 7% lower than the average Canadian forestry wage for both 1985 and 1986.

1.2.2.5 Production

The study region identified in Figure 1.1 includes the three

Table 1.6 Forestry Employment, 1985-1986.

	Estimated No. Employees (000's) 1985	Average Weekly Wage ($) 1985	Estimated No. Employees (000's) 1986	Average Weekly Wage ($) 1986
FORESTRY[a]				
Canada	55.3	546.66	50.0	566.98
Manitoba	1.1	470.97	0.8	540.53
Saskatchewan	0.6	508.57	0.6	535.32
Alberta	2.1	497.83	2.1	508.67
Prairies	3.8	492.46	3.5	528.17
Wood Industries (SIC 25)				
Saskatchewan	1.2	457.14	1.3	435.04
Alberta	4.6	471.62	5.0	478.79
Paper and Allied Industries (SIC 27)				
Alberta	2.6	619.98	3.0	630.23

[a] Includes the Forestry Services Industry and the Logging Industry only.

Source: Employment, Earnings and Hours
Statistics Canada
Labour Division
August 1986

Prairie Provinces and the Northwest Territories. This section defines the harvestable forest areas and the products which they produce. It also includes the imports and exports of wood products to and from these areas.

The total area of forest land for Canada is identified in Table 1.7 as 4.4 million km^2, of which 2.6 million km^2 is productive. Of this productive area, the prairies contribute 463,000 km^2 (17.5%) and the Northwest Territories contribute 210,000 km^2 (8%). The Government owns 440,000 km^2 (95%) of productive prairie forest lands and all of the forest land in the Northwest Territories. Private ownership on the prairies accounts for 4,000 km^2 which is less than 1% of the total forest land. Government forest land that is available for harvest makes up 73% and 86% of the forest land on the prairies and in the North, respectively.

The merchantable volumes of wood for each province for 1981 are defined in Table 1.8. The forests are categorized into age classes with the prairies and the Northwest Territories having mainly immature forest. Together, these two areas account for 26.8% of the immature and 8.2% of the mature wood in Canada. Of the total merchantable wood in Canada, the prairies and the Northwest Territories contribute 2,557 million m^3 (13%) and 700 million m^3 (4%), respectively. Softwoods in the study region make up 13% of all softwoods in Canada and hardwoods make up 35%.

The area harvested in each province is presented in Table 1.9 for the years 1975 to 1982. The average harvest over this seven-year period is 20,071 ha which is 2.6% of the total number of hectares harvested in Canada during 1975-1982. Of the area harvested in Canada for this

Table 1.7 Forest Area Classification, Canada, 1981.

(1 000 km^2)

Area Class	QUE.	ONT.	MAN.	SASK.	ALTA.	PRAIRIES	B.C.	YUKON NWT	OTHER	CANADA
Forest Land Inventoried										
Productive	533	377	140	89	216	445	458	210	179	2202
Unproductive	91	55	100	34	115	249	108	647	72	1223
Subtotal	624	432	240	123	331	694	566	857	251	3425
Forest Land Not Inventoried										
Productive	316	49	484	22	18	18	57	-	-	440
Unproductive		326	109	55	-	164	10	-	-	500
Subtotal	316	375	109	55	18	182	67	-	-	940
Total Forest Land	940	807	349	178	349	876	633	857	251	4364
Total Land	1357	891	548	570	644	1762	931	3724	502	9167
Water	184	177	102	82	17	201	18	137	39	755
Total Area	1541	1069	650	652	661	1963	949	3861	539	9922
Stocked, Productive, Non-reserved forest land										
Government	431	296	114	74	133	321	399	186	110	1746
Private	57	34	4	-	-	4	16	-	56	164
Other	-	-	-	-	-	-	-	-	-	-
Total	489	331	118	74	133	325	413	186	166	1910
Productive Forest Land										
Government	471	337	135	89	216	440	442	210	117	2019
Private	63	39	4	-	-	4	16	-	57	180
Other	-	-	-	-	-	-	-	-	3	3
Total	533	376	139	89	216	444	458	210	179	2202
Inventoried Forest Land										
Government	558	388	235	123	331	689	549	857	182	3222
Private	66	43	5	-	-	5	17	-	67	199
Other	-	-	-	-	-	-	-	-	3	4
Total	624	432	240	123	331	694	566	857	251	3425

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986 pp. 3-4.

Table 1.8 Gross Merchantable Volume of Wood on Inventoried, Stock Productive, Non-Reserved Forest Land, 1981.

	1 000 000 m^3									
Area Class	Quebec	Ontario	Manitoba	Sask	Alberta	Prairies	BC	Yukon/NWT	Other	Canada
By Age Class										
Regeneration	160	17	-	-	1	1	1	-	1	180
Immature	1149	2151	371	-	979	1350	1569	453	166	6738
Mature	2824	467	239	-	326	565	6272	341	561	11030
Overmature	-	563	25	-	110	135	-	1	78	777
Uneven-aged	-	-	-	-	-	-	-	-	23	23
Undetermined	-	316	49	484	22	506	18	5	385	896
Total	4133	3198	635	484	1438	2557	7842	700	1214	19644
Softwoods	3089	2075	439	293	781	1513	7438	529	926	15570
Hardwoods	1044	1123	196	191	657	1044	404	171	288	4074
Total	4133	3198	635	484	1438	2557	7842	700	1214	19644

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986 p. 6.

Table 1.9 Forest Area Harvested (ha).

Province	1975-76	1976-77	1977-78	1978-79	1979-80	1980-81	1981-82	Total
British Columbia	156,976	175,952	166,081	196,533	187,547	187,834	147,889	162,172
Alberta[a]	20,256	19,060	21,450	22,103	24,689	29,762	32,302	37,120
Saskatchewan	13,814	9,727	14,231	14,909	20,396	20,746	19,690	[19,700]
Manitoba[b]	[15,700]	[17,000]	[18,000]	[20,000]	24,600	24,600	18,900	20,400
Ontario	196,760	156,721	187,993	194,998	218,578	242,679	227,603	222,921
Quebec	135,094	181,737	193,295	226,127	241,826	245,000	250,000	195,000
Other	140,286	116,341	132,170	142,148	154,092	140,814	119,031	119,325
Canada	678,886	696,538	733,220	816,818	871,728	891,435	815,415	776,638

[a] In 1980-81,1981-82, and 1982-83, 6 720, 11 785, and 10 091 hectares were cleared of aspen under a special stand conversion program and were not harvested in the commercial sense.

[b] Numbers in brackets are estimates.

Source: D.H. Kunhnke & L.G.Grace. Silviculture Statistics for Canada, 1975-76 to 1982-83
Information Report NOR-X-275
Northern Forestry Centre
Canadian Forestry Service 1986 p.3

period, the prairie harvest was 10% of the total hectares. The annual area harvested in the Prairie Provinces increased during the period 1976 to 1980, but declined in 1980 to 1981.

The volume of industrial roundwood and fuelwood production for the Prairie Provinces is presented in Table 1.10. Alberta is the main contributor with an annual average of 5,552,000 m^3 produced over the period 1970 to 1983. Saskatchewan follows in production with an average of 2,815,000 m^3, while Manitoba produces only 1,785,000 m^3 of these products. Together, the three provinces contribute 7.3% to Canada's average annual roundwood production for the years 1970 to 1983.

Lumber production in Canada for the years 1970 to 1983 is categorized by province in Table 1.11. The average production of Manitoba, Saskatchewan, and Alberta lumber increased from 490,000 m^3 in 1970 to 826,000 m^3 in 1982; in 1982, this constituted 2.2% of the lumber produced in Canada.

The total wood pulp produced in Canada also increased over the years 1960 to 1984 (Table 1.12). The percent of Canadian production accounted for by the prairie provinces increased from 2.8% in 1960 to a peak of 5.4% in 1975; it then declined to 4.6% in 1983. Canada's total wood pulp production also increased over this period, rising to 21,123,000 t in 1984.

Paper and paperboard production for Canada is categorized by region in Table 1.13 for the years 1960-1984. Quebec, Ontario, and British Columbia are the major contributors with the other provinces in Canada making up an average of 15% of total production over this period. In 1984, the contribution to total production by other provinces dropped to 10%.

Table 1.10 Estimation of Roundwood Production by Province, Category, and Species Group, 1970-1983.

Year	Industrial Roundwood	Fuelwood	Total
		1 000 m^3	
MANITOBA			
1970	1075	184	1260
1971	1370	185	1556
1972	1654	182	1835
1973	1675	152	1828
1974	1936	165	2101
1975	1866	156	2022
1976	1572	170	1742
1977	1642	142	1784
1978	1670	133	1803
1979	1798	105	1903
1980	2228	107	2335
1981	1701	102	1803
1982	1374	124	1498
1983	1405	115	1520
SASKATCHEWAN			
1970	2120	256	2375
1971	2040	252	2292
1972	2455	184	2641
1973	2474	244	2718
1974	2567	210	2777
1975	2092	221	2313
1976	2639	227	2866
1977	2775	184	2959
1978	2707	156	2863
1979	3454	125	3579
1980	3211	119	3330
1981	3428	127	3555
1982	2402	124	2526
1983	2483	129	2612

Table 1.10 (Continued).

Year	Industrial Roundwood	Fuelwood	Total
		1 000 m^3	
ALBERTA			
1970	3991	152	4144
1971	3979	159	3138
1972	4803	90	4893
1973	5492	107	5599
1974	4965	93	5058
1975	4833	130	4963
1976	5505	122	5627
1977	6257	113	6370
1978	5624	102	5726
1979	6143	65	6208
1980	5865	68	5933
1981	6535	51	6586
1982	5581	133	5714
1983	7218	126	7344
BRITISH COLUMBIA[a]			
1970	54727		54726
1971	56550		56551
1972	56452		56451
1973	70137		70137
1974	60086		60086
1975	50078		50078
1976	69524		69521
1977	69970		69971
1978	75164		75164
1979	76194		76195
1980	74654		74654
1981	60780		60780
1982	56231		56231
1983	71445		71443

[a] Fuelwood included in industrial roundwood.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986 pp. 27-28.

Table 1.11 Lumber Production by Province, 1970-1983.

	1 000 m^3												
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982
QUEBEC	3785	4051	4975	5563	5276	4787	5731	6493	7572	8119	8059	7384	6517
ONTARIO	2002	2087	2279	2671	2831	2313	2773	3191	3828	4150	4468	4188	3864
MANITOBA	122	164	237	185	274	193	228	233	250	270	284	222	252
SASK	248	286	394	394	289	264	460	514	488	444	415	452	458
ALBERTA	1100	1180	1395	1901	1521	1003	1201	1477	1631	1622	1716	1945	1767
BC[a]	18084	21102	22439	24604	20634	17579	25086	28392	29584	30385	28247	24579	23428
OTHER	1245	1156	1280	1326	1299	1165	1342	1332	1534	1709	1807	1448	1167
CANADA	26588	30027	33000	36644	32124	27305	36822	41633	44887	46700	44995	40217	37452

[a] Includes Yukon and Northwest Territories.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986 pp. 29-30.

Table 1.12 Wood Pulp Production by Region, 1960-1984.

Year	Quebec	Ontario	British Columbia	Atlantic Provinces	Prairie Provinces	Total
			1 000 t			
1960	4054	2692	1927	1430	294	10398
1970	5898	3601	4100	2491	520	16610
1971	5666	3447	4409	2419	601	16543
1972	5893	3572	4576	2766	646	17453
1973	5591	3669	5337	3217	750	18564
1974	6353	3877	5267	3305	877	19679
1975	5198	2540	3998	2560	817	15113
1976	5882	3060	5320	2784	902	17946
1977	5860	3662	4831	2876	940	18168
1978	6632	4127	5426	2941	1027	20152
1979	6869	4322	5523	2956	1058	20728
1980	6356	4368	5782	3188	993	20687
1981	6858	4394	4995	3229	1096	20572
1982	6283	3753	4938	2626	914	18514
1983	6510	4217	5760	2784	925	20195
1984	6847	4443	5434	4399	[b]	21123

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[a] Canadian Pulp and Paper Association estimates.
[b] Included in the Atlantic Provinces.

Note: Approximately 76% used in production of paper and board in Canada.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Statistics
Government of Canada April 1986 p. 34.

Table 1.13 Basic Paper and Paperboard Production by Region, 1960-1984[a].

1 000 000 m

Year	Quebec	Ontario	British Columbia	Other Provinces	Canada
1960	3543	2313	1043	1195	8095
1970	5064	2883	1675	1631	11252
1971	4957	2830	1826	1545	11161
1972	5322	2935	1834	1791	11882
1973	5230	3233	2029	2093	12583
1974	5736	3404	1952	2128	13219
1975	4765	2099	1477	1725	10066
1976	5378	2592	1977	1844	11791
1977	5286	3086	1952	1813	12136
1978	5954	3317	2137	1967	13376
1979	6071	3553	2154	1863	13641
1980	5653	3522	2147	2063	13385
1981	6332	3562	1926	2136	13956
1982	5702	3153	1858	1764	12473
1983	6049	3388	2164	1870	13466
1984	6518	3920	2051	1458	13947

[a] Canadian Pulp and Paper Association estimates.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986 p. 36.

In Table 1.14, the value of exports and imports of forest products are listed by commodity group for the years 1970 to 1984. Forest product exports averaged 17% of total export value over this period. From 1980 to 1984, the percentage of forest product exports to total product exports declined to 14%. Imports of forest products as a percent of total imports into Canada remained around 2.2% over 1970-1984.

The values of domestic exports of forest products by province are presented in Table 1.15 for the years 1970-1983. The Prairie Provinces exported an average of 4% of total forest product exports in Canada over this period. The major exporting provinces are British Columbia, Quebec, and Ontario. There has been an increase in exports from each province over this period bringing the total value of exports in 1984 to $15.73 billion.

The 1984 domestic exports of forest products are listed by commodity group and by province or region of origin in Table 1.16. The majority of export value in each province is from Wood Pulp and Paper Products, except in British Columbia, which exports mainly wood fabricated materials. The prairies export 0.6% of total primary wood product exports. Wood fabricated materials from Saskatchewan, Alberta, and Manitoba constitute 4.5% of total Canadian exports. Wood Pulp and Paper Products exported from the prairies make up 4.6% of total exports. The total wood pulp and total paper product exports are 10% and 1.2%, respectively, of Canadian exports. Prairie exports account for 4.5% of the total forest product exports of $15.73 billion. The total forest product import value for Canada is $1.965 billion, and the prairies account for 5.8% of this total.

Table 1.14 Exports[a] and Imports of Forest Products (Value) by Commodity Group, 1970-1984. ($000 000)

	LUMBER								CANADA		
YEAR	Softwoods	Total	Plywood and veneer	Particle-board and wood building board	Wood-pulp	Other paper	Pulpwood & pulpwood chips	Other Forest Products	Total Forest Products	Total Products	Forest products (%)
A. EXPORTS											
1970	638	664	73	-	785	1277	38	121	2958	16820	17.6
1971	799	830	71	-	798	1258	36	123	3116	17820	17.5
1972	1128	1174	97	-	830	1380	27	142	3650	20150	18.1
1973	1559	1600	128	-	1082	1575	28	169	4582	25421	18.0
1974	1255	1292	107	-	1889	2151	27	165	5631	32422	17.4
1975	949	975	90	-	1834	2051	25	155	5130	33328	15.4
1976	1611	1653	102	-	2186	2381	34	229	6585	38475	17.1
1977	2339	2389	149	-	2158	2853	47	339	7935	44554	17.8
1978	3158	3230	212	-	2181	3504	63	434	9634	53183	18.1
1979	3821	3903	248	-	3083	4049	69	546	11898	65641	18.1
1980	3265	3368	237	-	3873	4699	117	548	12842	76159	16.9
1981	2916	3029	222	-	3819	5292	123	567	13053	83811	15.6
1982	2848	2954	215	-	3221	5102	106	590	12188	84530	14.4
1983	3896	3997	258	92	3049	5104	101	660	13261	90613	14.6
1984	4179	4296	273	155	3908	6213	96	848	15789	112496	14.0
B. IMPORTS											
1970	22	38	28	6	10	107	3	72	264	13952	1.9
1971	27	45	37	11	15	120	3	83	313	15618	2.0
1972	38	67	60	15	17	145	5	117	426	18669	2.3
1973	60	99	78	23	17	188	4	155	564	23325	2.4
1974	71	117	114	33	19	282	8	216	790	31722	2.5
1975	71	110	124	30	30	346	9	216	864	34716	2.5
1976	95	164	97	29	33	432	8	229	992	37494	2.6
1977	96	171	72	25	35	402	16	250	972	42363	2.3
1978	94	203	76	25	50	469	20	305	1147	50108	2.3
1979	127	271	89	26	79	546	27	390	1428	62871	2.3
1980	108	235	64	23	79	576	17	344	1338	69274	1.9
1981	130	276	113	29	83	722	20	385	1628	79482	2.0
1982	72	177	46	15	88	684	29	273	1302	67856	1.9
1983	123	281	88	21	86	876	20	268	1640	75608	2.2
1984	108	282	78	24	129	1107	22	324	1965	95842	2.1

[a] Including re-exports.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch

Canadian Forestry Service
Government of Canada
April 1986 p. 55.

Table 1.15 Domestic Exports[a] of Forest Products (Value) by Province or Region of Lading 1970-1983 and by Province or Region of Origin, 1984.

($000 000)

Year	Que.	Ont.	Man.	Sask.	Alta.	Prairies	BC[b]	Other	Canada
A. Province or region of lading									
1970	781	515	13	29	50	92	1220	348	2995
1971	779	498	16	32	53	101	1379	355	3112
1972	839	548	28	40	73	141	1708	409	3646
1973	906	662	36	51	92	179	2294	536	4578
1974	1210	857	42	58	145	245	2511	802	5626
1975	1197	747	38	56	167	261	2148	774	5127
1976	1336	904	44	49	188	281	3226	828	6575
1977	1604	1264	56	55	220	331	3782	945	7927
1978	2086	1566	73	78	219	370	4629	979	9629
1979	2601	1956	85	91	289	465	5696	1172	11890
1980	2937	2228	90	123	316	529	5669	1456	12819
1981	3404	2513	124	141	330	595	4756	1636	13003
1982	3347	2385	105	97	294	496	4590	1317	12133
1983	3301	2686	103	114	329	545	5453	1231	13218
B. Province or region of origin									
1984	4000	3270	146	146	415	708	6044	1707	15730

[a] Excluding re-exports.

[b] Includes Yukon and NWT.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986 p. 56.

Table 1.16 Domestic Exports[a] of Forest Products (Value) by Commodity Group and Province or Region or Origin, 1984.

($000)

Products	Atlantic Provinces	Quebec	Ontario	Manitoba	Sask	Alberta	Prairies	BC[b]	Canada
A. Primary Wood Products	25,242	15,539	2,951	216	254	1,794	2,264	309,993	355,989
B. Wood fabricated Materials	108,443	799,578	1,007,329	72,122	22,554	144,493	239,169	3,109,146	5,263,664
C. Wood Pulp and Paper Products	1,573,578	3,184,722	2,260,168	73,918	123,442	269,129	466,489	2,624,984	10,109,941
Total Wood Pulp	730,693	384,738	640,381	9,800	120,220	259,854	389,874	1,762,321	3,908,007
Total Paper Products	842,886	2,799,985	1,619,786	64,118	3,221	9,276	76,615	862,663	6,201,934
TOTAL FOREST PRODUCTS	1,707,263	3,999,839	3,270,448	146,256	146,250	415,416	707,922	6,044,123	15,729,594

[a] Excluding re-exports.
[b] Includes Yukon.

A. Includes logs, bolts, pulpwood/chips, and other primary products.
B. Includes lumber, shingles, shakes, veneer, plywood, and other wood products.
C. Includes newsprint, other paper and paperboard.

Source: Selected Forestry Statistics
Canada 1985
Economics Branch
Canadian Forestry Service
Government of Canada April 1986 p.57.

The preceding discussion and tables indicate that forestry is an important sector of the Canadian economy and that it is important to examine the economic impacts of climatic change on Canadian forests. However, it also indicates the relative unimportance of the study region in terms of economic activity - activity that shows up in GNP figures. Nonetheless, as is indicated later in this report, it is possible to evaluate economic benefits of increased forest growth, although it must be recognized from the outset that these benefits may not show up in market transactions and, hence, in GNP figures.

This chapter provides details of characteristics of the study area that are relevant to this study and lists study objectives. Chapter two consists of a literature review, emphasizing climatic change impact assessment and a review of the relevant literature in the topic areas of tree growth and physiology, direct effects of increased CO_2 levels, forest productivity, forest zonations, forest fires, insects and diseases, and economics. Chapter three consists of discussions of the availability and suitability of data and methodologies in the investigation of the possible impacts of climatic change. The remaining chapters provide preliminary results, conclusions, and recommendations for further work.

2 LITERATURE REVIEW AND DISCUSSION OF POSSIBLE IMPACTS OF CO_2-INDUCED CLIMATIC CHANGE

2.1 Introduction

Although a few studies have examined the potential effects of the expected climatic warming on agricultural crops (e.g. Parry et al. 1987; Arthur et al. 1987), very few have focussed on the boreal forest. Kauppi and Posch (1985) are among the few exceptions. Kates (1985) has provided an overview of climate impact assessment and refers to some relevant work in forestry. Other literature that is relevant are the biomass studies including Williams (1985), Williams and Masterton (1983), Williams et al. (1987) and Emanuel et al. (1985). The bibliography compiled by Peterson et al. (1983) is useful as it includes the references dealing with the impact of climatic variation on biomass accumulation in the boreal forest zone. Examining the effect of past warming can help estimate the effects of future warming.

The nature of the forestry and climatic change literature and data produces a mixing of spatial scales. For example, some of the work represents a small area such as that for a single tree. Alternatively, the few climatic change impact studies address large areas similar to that of some ecoregions. Climatic change data are only available for such large areas currently, and methods should be developed to attempt to bring these scales of approach towards agreement.

2.2 Direct Effects of CO_2-Enrichment on the Physiology and Growth of Commercial Boreal Forest Tree Species

The direct effects of enriched CO_2 on plants appear to be a result of effects on photosynthesis and upon water use efficiency (WUE) (e.g. Morison 1985; Tolbert and Zelitch 1983; Kramer 1981). Water use efficiency is based on the ratio of photosynthetic CO_2 uptake to transpiratory water loss. Generally speaking, carbon 3 (C_3) plants, which include all temperate and boreal tree species, increase in dry weight, height, diameter, leaf area and branching with increases in CO_2 up to at least 700 ppm (Kimball 1983). CO_2-enrichment provides a more abundant substrate for photosynthesis and stomatal resistance (controlling water loss) tends to increase with increasing CO_2. There is significant variation in response among species, so study of individual species is required to firmly establish results (Kimball 1985).

A difficulty in establishing direct responses of trees to high CO_2 is that no studies have followed the full life cycle of long-lived perennials like trees. Most studies have been short term (minutes to months) and most have concentrated on seedlings. Interestingly, it is with older trees where the first real evidence of a detectable, realworld response to increased CO_2 has been found. LaMarche et al. (1984) have shown an increase in diameter growth of old bristlecone pine trees during the last 150 years that corresponds to the timing of rapid increases in CO_2 levels following industrialization.

While controlled environment studies allow the determination of direct effects of CO_2-enrichment on physiology and growth of tree species, at least for young trees, it is important to remember that interactive effects with other limiting factors will often reduce the magnitude of observed CO_2 response. Increasing CO_2 may partly compensate for water stress or nutrient deficiencies (Norby et al. 1986; Morison 1985; Norby et al. 1984), but drought and nutrient shortages will still limit forest productivity (Kramer and Sionit 1985).

2.2.1 Boreal Tree Species that Have Been Studied Relative to Direct CO_2 Effects

Of the boreal tree species, only white spruce, trembling aspen and jack pine have received attention in CO_2 studies (Brown and Higginbotham 1986; Higginbotham 1983; Yeatman 1970). Data provided in these studies can likely be supplemented with some confidence by data for lodgepole pine (*Pinus contorta*) and bigtooth aspen (*Populus grandidentata*) (Higginbotham et al. 1985; Jurik et al. 1984) because of close genetic relationships. Data for white spruce are likely somewhat applicable to black spruce even though lack of hybridization between the two species suggests limited genetic closeness (Fowells 1965). Because of the limited information available, further discussion focuses on the four commercially important species in the study area (white spruce, black spruce, trembling aspen, jack pine and lodgepole pine).

2.2.2 Photosynthesis

Kramer (1981) states that initial response of photosynthesis to an increase in CO_2 concentration is an increase in rate of assimilation, unless light, moisture or some other factor strongly limits the process. He further suggests that rates tend to eventually drop towards those found at ambient CO_2 levels. No photosynthetic data are available at present for any of the four species under discussion. Some work, however, was done with lodgepole pine (Higginbotham et al. 1985) and this information is likely applicable to jack pine. Maximum net photosynthetic rates at 500 u $mol.m^{-2}s^{-1}$ photosynthetically active radiation (PhAR) were 4.5, 7.2, and 6.5 $mg.dm^{-2}h^{-1}$, respectively, for seedlings grown at CO_2 concentrations of 330, 1000 and 2000 ppm for four months. These rates are similar to those reported earlier for lodgepole pine by Dykstra (1974). While the rates are not greatly different, it is important to note that the plants had apparently acclimated to enriched CO_2. Km values (substrate level at one-half Vmax) for radiation were 280, 491 and 553 u $mol.m^{-2}s^{-1}$ for trees grown at 330, 1000 and 2000 ppm, respectively. Km values for CO_2 were 1005, 1720, and 640 ppm for trees grown under the same CO_2 conditions as above. CO_2 exchange of bigtooth aspen in Michigan at 1900 ppm was 151% of that at 320 ppm in 12 to 14 m trees (Jurik et al. 1984). Measurements were short-term and so probably reflect the maximum effect of CO_2 increase.

2.2.3 Water Use Efficiency

In general, water use efficiency (WUE) improves with increased CO_2 levels as a result of stomatal closure (Morison 1985). Pearcy and Bjorkman (1983) suggested, however, that plants respond in one of three ways: 1) little or no stomatal response, 2) partial closure, or 3) a strong closing response. Leaf resistance in lodgepole pine shortly after watering averaged 4.5 s cm^{-1} at CO_2 levels of 330, 1000 and 2000 ppm (Higginbotham et al. 1985). WUE can still be said to increase because there is no increase in transpiration, but there is an increase (at least short term) in photosynthetic rate. Presumably this would result in a greater ability for lodgepole pine to occupy dry sites.

Stomatal conductance in bigtooth aspen decreased by about half as CO_2 concentration increased from 300 ppm to 600 ppm, suggesting a fairly strong stomatal response could be expected for trembling aspen. WUE increased by approximately 100% over the same CO_2 interval. Brown (1987 pers. comm.) found that stomatal resistance of well-watered trembling aspen increased by about three times when plants were grown at 759 ppm

CO_2, as compared to plants grown at 340 ppm.

The extent to which WUE is increased by enriched CO_2 probably depends upon the relative shade-tolerance of a species. There is generally a relationship between stomatal conductance and tolerance. Wuenscher and Kozlowski (1970) showed that conductance (and photosynthetic rate) was greater for intolerant hardwoods than for tolerant ones. Spurr and Barnes (1980) reported the following tolerances for the species of interest here:

Species	Tolerance	Scale (0 to 10)
Trembling aspen	Very Intolerant	0.7
Jack pine	Very Intolerant	1.8
Black spruce	Mid-Tolerant	6.4
White spruce	Mid-Tolerant	6.8

Whether WUE improves more for the intolerant or the mid-tolerant species under high CO_2 depends on the relative influence of CO_2 on stomatal conductance. Morison (1985) suggested that there is a linear relationship between conductance and CO_2 concentration and that species with high conductance under ambient CO_2 will be most sensitive to CO_2 increases. Brown's data (mentioned previously) suggest that trembling aspen responds very strongly to a doubling of CO_2. One would assume that pine will respond similarly, although data for lodgepole pine (Higginbotham et al. 1985) put this statement in question. It is assumed that the spruces would respond least and, therefore, show the least change in WUE.

The increase in WUE calculated using photosynthesis and transpiration measurements of single (or a few) leaves probably cannot be extrapolated to whole plants or to stands of trees. Other factors such as mutual shading within tree crowns and the increase in total leaf surface area which often occurs in high CO_2 environments tend to attenuate the response. For example, Rogers et al. (1983) showed a 160% increase in transpiration efficiency of sweetgum (*Liquidambar styraciflua*) with a doubling of CO_2, based on single leaf measurements. Morison (1985) predicted that 30 to 50% improvement is more likely for whole plants.

2.2.4 Growth

As indicated earlier, growth (especially biomass) tends to increase with increasing CO_2. Yeatman (1970) found increases of 61 and 40% in shoot dry weight of 3-week old white spruce and jack pine seedlings grown at 900 ppm as compared to ambient conditions.

Biomass components for lodgepole pine grown for five months at 330, 1000 or 2000 ppm CO_2 are shown in Figure 2.1. Large increases in weight of roots and leaves were found. Seedlings grown at 1000 ppm CO_2 exhibited the greatest growth with 2000 ppm trees in an intermediate position.

The effects of increased CO_2 on leaf area production are shown in Figure 2.2. As Kramer (1981) pointed out, much of the increased productivity seen under elevated CO_2 may result from increases in leaf area. Increased production is still possible with increased leaf area even if photosynthetic rates return to the same level as those under ambient conditions of CO_2.

Biomass production of white spruce seedlings grown at 330, 600 or

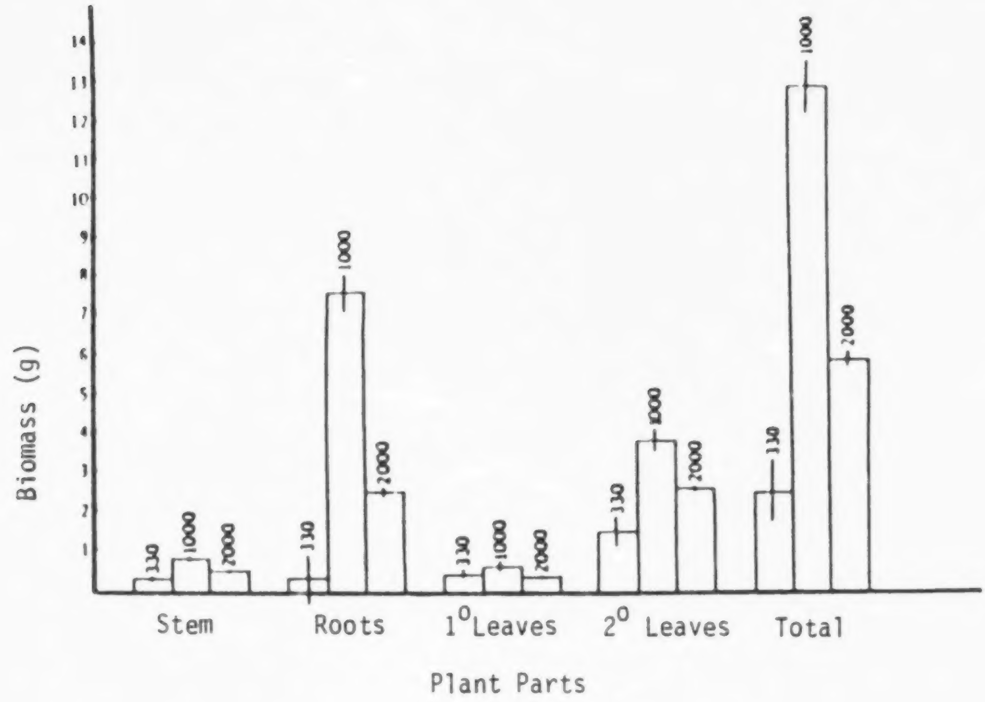

Figure 2.1 Biomass Components of Lodgepole Pine Seedlings Grown at 330, 1000, or 2000 ppm CO_2. Lines on bars show ± 1 standard error of the mean. (Higginbotham et al. 1985).

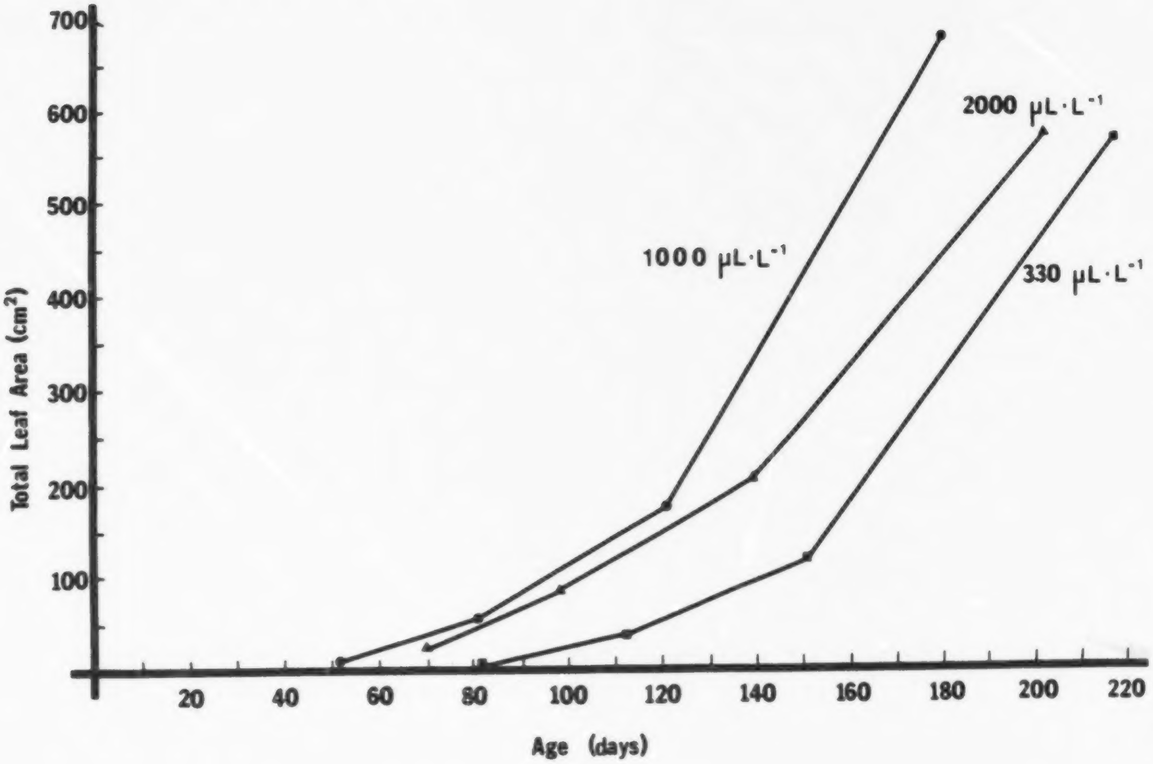

Figure 2.2 Production of Total Leaf Surface Area by Lodgepole Pine Seedlings Grown at 330, 1000 or 2000 ppm CO_2 (Higginbotham et al. 1985).

1000 ppm CO_2 for a period of four months are illustrated in Figure 2.3 (Higginbotham 1983). Maximum growth response was at 600 ppm, with seedlings grown at 1000 ppm in an intermediate position. Again, largest increases over ambient were seen in root biomass and leaf production.

Brown and Higginbotham (1986) found that CO_2 enrichment (750 ppm) significantly increased biomass, leaf area and height of seedlings of trembling aspen, but the effects were temporary. It is felt that mineral shortages after that time may have overwhelmed the effects of increased CO_2. In the same study, increased CO_2 had significant effects on biomass of white spruce but had no effect on height, leaf area or branch number. CO_2-enrichment increased root mass of white spruce seedlings grown in a low nitrogen medium.

All of the studies providing data on the effects of CO_2-enrichment on growth are relatively short-term. All of them were carried out on seedlings. No information is available to suggest the long-term importance of the results found for seedlings. In theory, increased growth rates of young plants should be compounded over time, producing mature, harvestable trees in shorter rotations than currently used. However, other species in natural systems may respond even more than the trees, causing severe competitive problems. Early crown closure might create early intra-specific competition, and the response of trees grown for many years in high CO_2 to silvicultural treatments of various kinds is unknown.

2.2.5 Reproduction

Kramer (1981) pointed out that the direct effects of high CO_2 on reproduction vary strongly with species. He cited examples of delays in

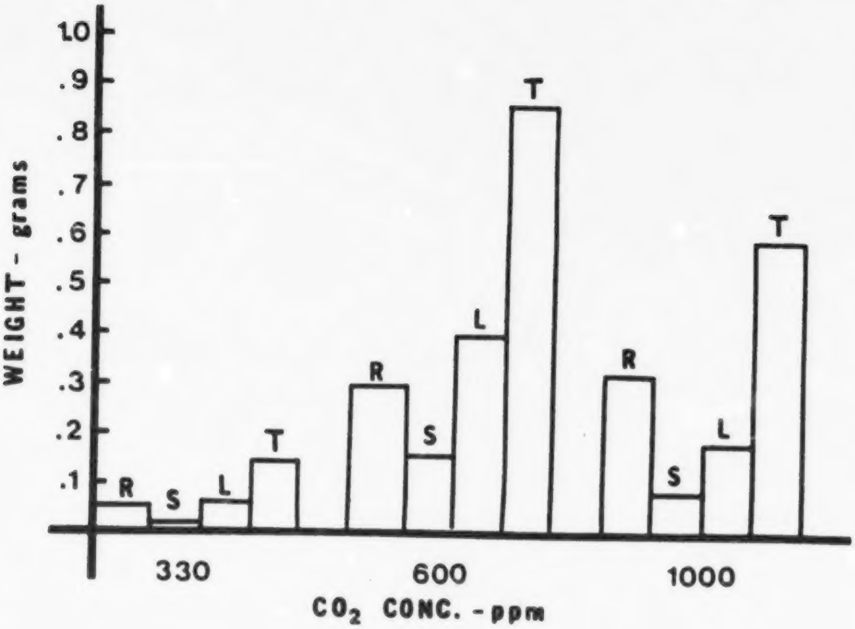

Figure 2.3 Biomass of Roots (R), Stems (S), Leaves (L), and Total Plants (T) for White Spruce Seedlings Grown at 330, 600 or 1000 ppm CO_2 (Higginbotham 1983).

floral initiation and, in other instances, flowering has been promoted under otherwise noninductive conditions. No information is available for any of the four species under discussion here; in fact, little, if any work has been done with perennial plants.

Grant Lipp and Ballard (1959) reported that seed dormancy in small-seeded legumes can be broken by treatment with high CO_2 (2.5%). However, in our studies with lodgepole pine and white spruce, CO_2 levels up to 2000 ppm had no effect on germination of these species (Higginbotham, unpublished).

2.3 CO_2-Induced Climatic Change Effects on Plant Physiology and Growth

Solomon and West (1985) developed an extensive listing of climatic and human variables necessary to document in order to project effects of CO_2-induced climatic change on forests, or the species found in the forest (Table 2.1). It was developed with temperate forests in mind but gives an idea of the complexity of the problem.

Additional variables need to be added to make Table 2.1 complete enough for use in boreal situations. It is also clear from Table 2.1 that the life cycle stage of trees is critical for proper projection, and little is known about physiological and growth responses of trees beyond the seedling stage. This is a good start, however, as the reproduction and establishment of new forests is important to the development and planning of future forests.

The climatic or site factors of greatest importance are generally those related to temperature and precipitation. They include air temperature, especially growing season temperatures, soil temperature, soil moisture and relative humidity. Nutrient availability is also very

Table 2.1 Variables, Data and Ecological Responses that Must be Documented to Project Effects of CO$_2$-Induced Climatic Change on Forests.

Environmental Variables	Affected Organisms, Life-Stages, or Environmental Variables	Primary Responses	Secondary Responses
Climate Variables			
Temperature Variables			
Frequency, Intensity of Winter Low Temperatures	Saplings	±Death of saplings	
	Trees	± Loss of buds, branches	Loss of reproduction, tree damage
Frequency, Intensity of Spring Frosts	Spring-germinating seeds	± Death, by species	
	Trees	± Defoliation	± Growth of tree, by species; mortality
Cumulative Growing Season Warmth	Saplings, trees	± Growth of tree, by species	± Increased disease* mortality,
	Soil biota	± Nutrient release rates	± Growth of tree, by species
Frequency, Intensity, Length of Heat Waves in Midsummer	Seedlings	± Death, by species	
	Fire frequency	± Death, damage, by species	± Increased disease* mortality
Frequency, Intensity of Fall Frosts	Fall-germinating seeds	± Death, by species	
Precipitation Variables			
Frequency, Length of Flooding	Seedlings	± Death	
	Saplings, trees	± Death, slowed growth, by species	± Increased disease* death by species
Frequency of Spring Soaking Rains	Seedlings	± Death from soil biota, by species	
Growing Season Precipitation as Soil Moisture	Seedlings	± Death if too little/too much, by species	
	Saplings, trees	± Growth of tree, by species	± Increased disease* death by species
	Soil biota	± Nutrient release rates	± Growth of trees, by species
Frequency, Intensity of Growing Season Droughts	Seedlings	± Death, by species	
	Mature Trees	± Slowed, stopped growth, by species	
	Fire frequency	± Death, damage; reproduction by life stage and species	± Increased disease, * death by species
Intensive Wind Storms, Ice Storms	All trees, largest trees, shallow-rooted trees	± Death, damage; enhanced reproduction by species	± Increased disease, * mortality
Human Variables			
Land Use	All trees	Homogeneous age structure of stands	Increased disease * stress changes to the stand level
CO$_2$ Concentration	Seedlings	Increased growth and carbon storage, enhanced drought-tolerance	Increased seedling survival; other responses in other life stages possible
	No other tree life stages measured	Unknown	
Acidic Precipitation	Seedlings, saplings, trees	± Growth of tree by species ± Nutrient release rates	± Increased disease, * mortality ± Growth of tree, by species
Gaseous Pollutants	Seedlings, saplings, trees	± Growth of tree by species	± Increased disease, * mortality

*Disease denotes changes in tree growth due to some combination of changes in frequency or intensity of attacks by bacteria, fungi, and/or insect populations.

Source: Solomon and West (1985).

important and is considered in the following sections.

2.3.1 Temperature Effects

Photosynthesis, the process on which forest production is ultimately based, has a well-known dependence on temperature. The rate of gross photosynthesis rises with temperature to some maximum (limited by the supply of CO_2), and declines only at high temperatures which inactivate the photosynthetic enzymes. Respiratory consumption of photosynthetic products also rises with temperature. The shape of the curves of gross photosynthesis and respiration is such that the difference between them, or net photosynthesis, reaches an optimum at moderate temperatures, while beyond some higher temperature, respiration exceeds photosynthesis (Larcher 1975). For black spruce, the optimum temperature for net photosynthesis is about 15°C according to several studies (van Zinderen Bakker 1974; Vowinckel et al. 1975; Black and Bliss 1980), while for balsam fir, Fryer and Ledig (1972) cite optimum temperatures ranging from 15 to 25°C.

However, this photosynthesis/temperature response is not as crucial for assessing the effects of climatic change as it might appear. Near-optimum net photosynthesis may occur over a broad range of temperature. Vowinckel et al. (1975) found that subarctic black spruce maintained at least 90% of their maximum net photosynthetic rate over a range from 9 to 23°C; even in this cold climate, it was concluded that photosynthesis was mainly limited by light, and not by temperature.

Moreover, plants have a substantial capacity for acclimation, that is, for adjustment of their response to temperature as temperature changes (Larcher 1975; Berry and Bjorkman 1980). In labrador-tea (Ledum groenlandicum), a widespread boreal shrub, Smith and Hadley (1974) found that pretreatment at different temperatures produced corresponding differences in the optimum temperature for net photosynthesis, while having little effect on the maximum rate of net photosynthesis. Strain et al. (1976), Mooney and Harrison (1970) and others have shown that photosynthesis is a flexible process. The optimal temperature for photosynthesis tends to shift with prevailing temperatures. For example, maximum photosynthesis is expected to occur at a lower temperature in spring than in summer. This presumably helps to maximize annual productivity. Certainly this process will assist in adapting trees to climatic changes in temperature. Ultimately, genetic change will also occur.

In addition to this plasticity in the responses of individual plants, there may be genetic variation among local populations in their response to climate. Fryer and Ledig (1972) collected seeds from balsam fir at different altitudes on a New England mountain, and grew seedlings from them under uniform conditions. The temperature optimum for net photosynthesis declined with altitude of origin at a rate similar to the expected decline of temperature with altitude. Under a changing climate, one would expect a gradual migration of these ecotypes in order to maintain the close adaptation of the local population to its climate.

Temperature extremes may be more important than normal growing season temperatures for net photosynthesis (Waring and Schlesinger 1985). Frost has a suppressive effect on photosynthesis which persists even after warmer temperatures return (Larcher 1975; Waring and Schlesinger 1985). For boreal tree species, recurrent, increasingly severe night frosts in the fall cause a progressive reduction in photosynthetic rate the following day, accompanied by the process of cold-hardening which enables the tree's tissues to survive low temperatures. Finally the tree becomes fully dormant and photosynthesis ceases (van Zinderen Bakker 1974). Thus, the length of the period of above-freezing temperatures is crucial for the net photosynthesis of plants (Larcher 1975).

The actual degree of winter cold is of little importance for boreal tree species, which, once fully hardened, can survive any temperature they encounter. However, winter cold does appear to play a role in excluding some of the temperate deciduous forest species from the boreal zone (George et al. 1974). Warmer winters would allow these temperate species to expand northward and compete with boreal species. Warmer winters can conceivably also cause the southern limits of some species to move northward. Many woody plants have a "chilling requirement," that is, a requirement for a certain period of cool (not necessarily freezing) temperatures that must be met before winter dormancy will end (Salisbury and Ross 1969). However, given the long, severe winters of the boreal zone, drastic climatic warming would be required before failure to meet the chilling requirement would become a problem.

Temperature also affects the phenology, or seasonal development, of the plant. A sufficient period of warm temperatures (often expressed by the accumulation of "degree-days" above some threshold temperature) is required for the opening of dormant winter buds and the development of reproductive structures (Sarvas 1970; Kramer and Kozlowski 1979). With bud-opening, new leaves begin photosynthesis, so the control of phenology by temperature has an indirect effect on photosynthetic production. Evergreens have an advantage over deciduous plants in the short boreal growing season because the old leaves can begin photosynthesis in the spring before buds open to form new leaves, effectively extending the photosynthetic period a month or more (van Zinderen Bakker 1974; Oechel and Lawrence 1985). However, van Zinderen Bakker (1974) found that maximum photosynthetic rates in black spruce do not occur until the new needles are fully expanded, implying that phenology is important for the total production of evergreens too.

An important instance of the control of tree growth by temperature is the existence of high-latitude or high-altitude timberlines, beyond which trees cannot survive. Timberlines seem to be correlated with summer temperatures (Tuhkanen 1980), but the stresses preventing trees from growing beyond them seem to be due to winter desiccation (Tranquillini 1979). The best supported theory for the occurrence of alpine timberlines relates the short, cool, growing season to delayed opening of buds and incomplete development of the cuticle (the protective layer around a leaf), which leads to winter desiccation (Tranquillini 1979). Black and Bliss (1980) also found that summer temperatures at the Arctic timberline are too cool for seed-germination in black spruce.

Air temperature influences all enzyme-mediated biochemical reactions in the plant including photosynthesis and respiration. Most of the temperature mediated biochemical reactions in trees occur in the leaves. Leaf temperature, at least under low wind speeds, is usually higher than air temperature during the day (Gates 1965) so the physiological effects of increased air temperature can be expected to be enhanced. It is possible that shoot elongation may begin earlier, and that the probability of frost damage may be as great, except earlier in the year.

The previous discussion does not distinguish between the effects of air temperature and soil temperature. However, controlled-environment experiments have shown that tree growth at a given air temperature can vary with different soil temperatures (Cleary and Waring 1969). Cold soils are a critically important growth-limiting factor in the boreal forest. Normally, soil temperature must be greater than 5°C before root growth begins in spring, and shoot growth is dependent on the onset of root growth.

In addition, water uptake (and associated nutrient uptake) is restricted under cold soil conditions (Babalola et al. 1968). Wet soils, which are common in many parts of the boreal forest, are the slowest to warm up in spring, because of the high latent heat of fusion of water. Black spruce growing on wet soils in Alberta have delayed bud-burst in spring, because of slow thawing of the soil (van Zinderen Bakker 1974). At the forest-tundra interface, permafrost limits the survival of trees.

Under warmer air temperatures all of these soil temperature factors can be expected to be improved. However, if the warmer climate is accompanied by lower precipitation, there may be less snow cover to insulate the soil in winter. This would lead to deeper soil frost, and therefore to slower initiation of growth in spring. The combination of rising air temperatures in spring, with soils that are still frozen, often leads to desiccation injury in conifers, because the roots cannot absorb water to replace that evaporated from leaves. This could become a more serious problem under a warmer, drier climate.

2.3.2 Precipitation Effects

Precipitation affects plants indirectly, as an input into stored soil moisture available for plant uptake. Soil moisture is necessary for cell enlargement, chemical reactions and transpiration in plants. demand for transpiration. The amount available depends on precipitation and soil textural and drainage factors. Thus, the effect of precipitation varies greatly with landform and soil. In assessing example, by considering only mesic sites (those which are intermediate in moisture retention) (Lemieux 1961).

One would expect a warmer climate to produce a greater evaporative demand and perhaps lower relative humidity. Patterns of precipitation are difficult to predict using available general circulation models, so it is difficult to assess the magnitude of these potential problems (Solomon and West 1985).

Deficiencies in available soil moisture have many physiological effects on plants (Kramer 1962). The most important immediate effect is partial closure of the stomata through which leaves exchange gases with the atmosphere, a response which reduces evaporative water loss. This also rapidly reduces the diffusion of CO_2 into the leaves and so reduces net photosynthesis. Prolonged water deficit leads to complete stomata closure and to reduced hydration of the cytoplasm, and thus to cessation of photosynthesis (Larcher 1975; Waring and Schlesinger 1985).

There seems to be little information available on the incidence of moisture stress in boreal species. Vowinckel et al. (1975) and Black and Bliss (1980) conclude that there is little reduction in photosynthesis due to moisture stress in mature black spruce near the Arctic timberline, although the latter study found that seed germination and early survival of seedlings may be reduced by moisture stress. Black spruce in central Alberta did experience mid-day stomatal closure due to moisture stress, which reduces photosynthesis (van Zinderen Bakker 1974).

Excess soil water also limits tree growth by filling the soil pores and so reducing oxygen supply to the roots. Wet soils are widespread in the boreal forest, and often lead to development of peatlands with slow tree growth. A warmer climate with a drier climatic moisture balance could reduce the area of wet soils and accelerate the decomposition of peat. Thus growth increases on wet soils could help to compensate for growth losses on dry soils under such a climatic change.

Atmospheric water vapour is also a consideration. Larcher (1969) says that, in general, the relative humidity must be greater than 70% for "really effective" CO_2 uptake. Presumably, the strong vapour pressure gradient between leaf and air under relative humidities less than 70% leads to partial stomatal closure. Higher average air temperatures may lead to reduced average relative humidity and possibly reduced CO_2 uptake. Thus climate also has an effect on the utilization of CO_2.

2.3.3 Effects of Climate on Soil Processes

Another important effect of climate on plant production occurs indirectly, through soil processes. Plants require soil nutrients that must be recycled from dead plant material through the process of decomposition. The rate of decomposition increases with temperature and moisture supply (Meentemeyer 1978). The cool climate of the boreal zone leads to accumulation of undecomposed organic matter in which nutrients are locked up, causing nutrient deficiency in many boreal forests (Miller et al. 1983; Oechel and Lawrence 1985). Physiologically, this means that the growth of the plant is limited, not by photosynthesis of new carbohydrates, but by the supply of other constituents (nitrogen, phosphorus, sulfur, etc.) needed to convert those carbohydrates into the proteins, nucleic acids, etc. which make up new growth. Climatic warming should, therefore, have a beneficial effect on boreal production due to acceleration of nutrient cycling.

Nutrient availability is a function of soil supplies, mineralization rates, weathering rates and rate of decomposition of organic matter. The amounts required depend on species, growth rates and stand density. Mineralization rates and decomposition should increase in relation to increased temperature and moisture status.

2.3.4 Physiological and Growth Responses to CO_2-Induced Climatic Change with Particular Emphasis on Principal Boreal Tree Species

This section attempts to evaluate the effects of the factors discussed previously on photosynthesis, respiration, transpiration, nutrient requirements, regeneration and growth of white spruce, black spruce, jack pine and trembling aspen.

2.3.4.1 Photosynthesis

White Spruce

Like many relatively shade-tolerant tree species, maximum photosynthetic rates of white spruce are quite low. Clark (1961) found rates of 3 to 5 $mg.dm^{-2}h^{-1}$ of CO_2 uptake in the eastern part of the range of the species. His study focused on the light response of photosynthesis but showed that the optimum temperature for the process was near 20°C, as is the case for the majority of C_3 plants.

While no data were found to suggest the effects of soil temperature on photosynthesis of white spruce, or any of the other species, Babalola et al. (1968) found a reduction in photosynthesis of at least 50% with a reduction in soil temperature from 27 to 10°C in radiata pine (Pinus radiata). Delucia (1986) found that root temperature had no effect on net photosynthesis of Engelmann spruce (Picea engelmannii) seedlings between 10 and 20°C. Photosynthesis (and stomatal conductance) declined rapidly at root temperatures less than 8°C. Engelmann spruce is a close relative of white spruce. Probably white spruce and other boreal species can endure colder soils than radiata pine without significant reduction in net assimilation and will probably react like Engelmann spruce. Therefore, it is likely that warmer soils, in addition to the direct effect of CO_2 on photosynthesis, will improve productivity.

Tear (1979) found significantly less uptake of $^{14}CO_2$ by first year white spruce seedlings which were watered on a 12-day cycle compared to those watered every three days. Lopushinsky and Klock (1974) showed that stomatal closure was virtually complete when soil water potential reached -10 to -12 bars in Engelmann spruce. With stomata closed, one can presume that photosynthesis will be near zero. Higher temperatures combined with potentially reduced precipitation inputs could make soil moisture an even greater limiting factor to the production process in white spruce with increased CO_2 in the atmosphere.

Black Spruce

Black spruce is a species which increases in dominance as one moves northward in the boreal forest. Some have suggested that the species is well-adapted to harsher climates (e.g. Black 1977). However, it would probably do better in more moderate climates except that it is a poor competitor. This is probably why it is relegated to very wet (muskeg) sites throughout much of its range in the Prairies.

Extensive measurements of photosynthesis vs. temperature were made with black spruce in two studies. Black (1977) studied the species at its northern limit and van Zinderen Bakker (1974) worked in central Alberta. The results show little difference even though the latitudinal differences in the two sources are great (Table 2.2). Black's results show a flatter curve at the peak than van Zinderen Bakker which suggests the more northerly population would be less affected by increasing

Black (1977) also studied the effects of soil moisture on photosynthesis. A soil water potential of -15 bars reduced net photosynthesis by 50%; at -25 bars net photosynthesis was zero. If precipitation is decreased and temperature is increased as a result of CO_2 enhancement, soil moisture levels will likely decrease and productivity of black spruce could be reduced substantially. Some drying of very wet sites might lead to an overall production increase as a result of improved root aeration and perhaps increased soil temperatures.

Jack Pine

Diagnostic information to describe the photosynthetic responses of jack pine to temperature and moisture appears to be lacking. However, Dykstra (1974) completed a thorough study of CO_2 assimilation in lodgepole pine which likely can be applied to jack pine. Two year old

Table 2.2 Comparison of the Rates of CO_2 Uptake ($mg.dm^{-2}h^{-1}$) Versus Temperature for Two Studies.

Study[a]	Temperature (°C)							
	0	5	10	15	20	25	30	35
Black	2	2.5	3	5	5	4	3	2
VZB	2	3	4.5	6	4.5	2.5	1.5	--

[a] Black and VZB indicate the sources Black (1977) and van Zinderen Bakker (1974).

seedlings from the interior of British Columbia were used in the study. Figure 2.4 shows the effects of leaf temperature on net photosynthesis and upon stomatal and mesophyll resistance under well-watered conditions. Photosynthesis shows a peak at about 20°C, a response common to many C_3 plants. The peak is relatively flat so growing season temperatures a few degrees higher apparently have little effect on productivity. Given that early morning and late afternoon temperatures are often less than optimal under current conditions, a warmer scenario might produce a longer photosynthetic day at or near optimal temperatures.

The effects of moisture on net photosynthesis of lodgepole pine are shown in Figure 2.5. Net CO_2 uptake reaches zero at -15 bars plant water potential. Soil water potential would be somewhat higher (less negative). Lopushinsky (1975) showed that stomatal closure is more or less complete by -10 bars soil water potential, which is not significantly different from these results.

Trembling Aspen

Bourdeau (1958) reported photosynthetic rates for trembling aspen in the range of 20 to 21 mg CO_2 $dm^{-2}h^{-1}$. These rates are substantially higher than those reported by Lawrence and Oechel (1983b) for Alaskan aspen (Figure 2.6). However, peak rates are still as high in the Lawrence and Oechel study as those reported for pine above. Note the relatively minor effects of soil temperature on CO_2 uptake. Peak photosynthesis is again at about 20°C, but the peak is quite broad.

Lawrence and Oechel (1983a) showed the very strong effect of soil temperature on root respiration. Root respiration reflects growth and

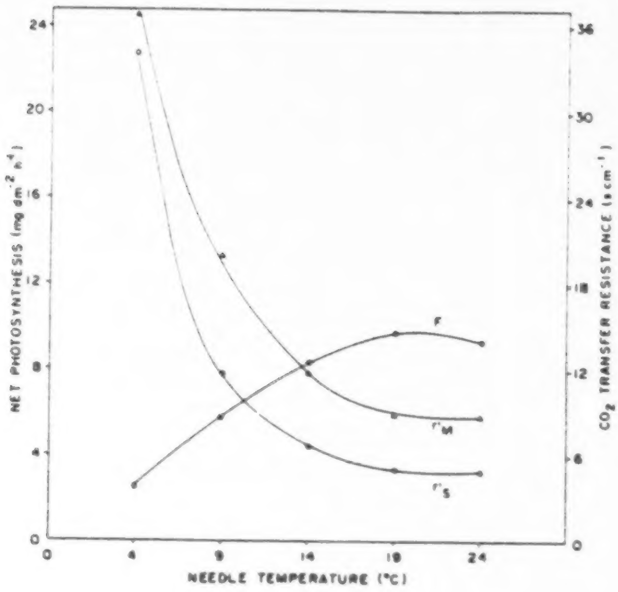

Figure 2.4 The Influence of Needle Temperature or Net Photosynthesis (F) and Stomatal (r_s) and Mesophyll (r_m) Resistances to CO_2 Transfer (Dykstra 1974).

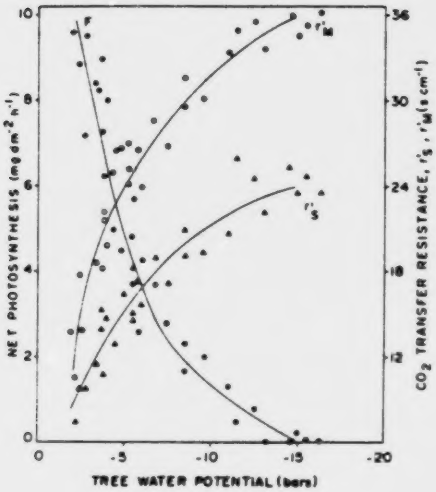

Figure 2.5 Net Photosynthesis (F) and Stomatal (r_s) and Mesophyll (r_m) Resistances to CO_2 Transfer in Relation to Plant Water Potential (Dykstra 1974).

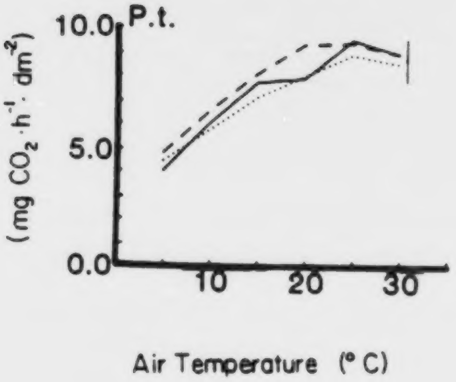

Figure 2.6 Soil Temperature Effect on Air Temperature Response Curves for Trembling Aspen (*Populus tremuloides*). Soil temperature treatments were 5°C (...), 150°C (---) and 25°C (___). (Lawrence and Oechel 1983b).

maintenance use of carbon. An increase of soil temperature from 5 to 25°C caused a three-fold increase in rate of respiration for trembling aspen. This indicates that significantly more carbon will be required as soils warm, reducing the overall increase in productivity which might be predicted based on direct effects of CO_2 on photosynthesis.

No specific data on the effects of moisture stress on photosynthesis in trembling aspen were found. The effects, however, would likely be very similar to those described for lodgepole pine. This assumption is based on the ecological similarities between the two species.

2.3.4.2 Respiration

While no attempt is made to compare rates of respiration of the four species because of lack of data, it is important to discuss this physiological process in general terms. Respiration (in this case dark respiration; photorespiration will not be discussed) is the process whereby photosynthetic products are metabolized to release the chemical energy stored during the photosynthetic reduction of CO_2. It is an enzyme-driven process which is highly temperature dependent. Respiration increases with temperature but in an exponential fashion. Within the range of "normal" growing temperatures (5 to 35°C) rate of respiration doubles with an increase in temperature of about 10°C (Salisbury and Ross 1978). There is a high likelihood, however, that respiration will acclimate to temperature change, and might reduce its expected increase.

Warmer air temperatures are expected, then, to lead to greater carbohydrate use for plant maintenance, leaving a lower percentage for production of such structural material as cellulose. This is likely to have its greatest impact on older trees where the ratio of nonphotosynthetic to photosynthetic tissue increases. At the extreme, this could lead to shortened life cycles for the trees, although acclimation, genetic change and uncertainty about the long-term maintenance of increased photosynthesis under high CO_2 make the question unanswerable at this point.

2.3.4.3 Water Use

Because of the role of stomatal control in regulating both CO_2 uptake and water loss, some of the factors of importance here were discussed earlier. In general, higher temperatures produce greater humidity that create stronger vapour pressure deficits between leaf and air. Presumably, the "transpiration season" will also be lengthened in both spring and fall.

As suggested earlier, jack pine, and trembling aspen, which are both pioneer species, can be considered conservative in their water use habits. Stomatal closure occurs while soil water potential is still relatively high. Black spruce, which may occur at both extremes of the wet to dry moisture gradient, probably reacts similarly. Mayo (pers. comm.) studied jack pine water relations on sandy sites in northeastern Alberta. He found a direct, linear response between vapour pressure deficit of the air and stomatal resistance. This, he suggested, is a very conservative mechanism; stomatal closure does not wait for a plant water potential trigger. Aspen and black spruce probably respond similarly.

Lopushinsky and Klock (1974) found that Engelmann spruce closed stomata relatively early (at about the same plant water potential as lodgepole pine). Anderson (unpubl. Ms.) found that white spruce closed its stomata at lower water potentials than jack pine. These two, somewhat contradictory, bits of evidence suggest that white spruce is probably less conservative overall than the pioneer species but it is probably more conservative than later successional species such as balsam fir.

The result of these characteristics is that if we assume somewhat drier atmospheric conditions under enriched CO_2, we can expect more frequent stomatal closure in these four species. This may not be true if these four species growing in the field experience partial, CO_2-induced stomatal closure.

It is important to remember that expected control of water loss may vary greatly depending on the genetic qualities of different populations of species. Dix and Swan (1971) and Day (1972) have shown that white spruce may be considered a pioneer species in some parts of its range (e.g. Candle Lake, Saskatchewan) and a climax, shade requiring species in other parts of its range. (e.g. southwestern Alberta). The degree of stomatal control over water loss probably varies between the two areas mentioned. Tobiesson and Kana (1974) showed that trembling aspen growing on moist sites in east-central New York state did not close stomata even at xylem pressure potentials as low as -30 bars. Stomata of bigtooth aspen from drier sites in the same area had tightly closed stomata at the same water potential. Site moisture apparently can be a strong or a weak selection pressure depending on its relative importance as a limiting factor.

2.3.4.4 Nutrients

Nutrient requirements of the four species under consideration here are not particularly high. Watson et al. (1980) suggested that the requirements of lodgepole pine (jack pine) and trembling aspen are low and that those of white spruce are moderate. While they did not discuss black spruce, one can assume requirements are also low, given the types of sites (very wet and very dry) on which the species is normally found. Low nutrient requirements do not necessarily mean that the species would not do better with more. All of these species have been shown to respond positively to fertilizer treatment. They can, however, survive with modest nutrient amounts present.

If nutrient levels become limiting, how great are the direct effects of CO_2-enrichment? These direct effects are discussed in Section 2.2. Canham and McCavish (1981) showed that combined increases in CO_2 and fertilizer in a nursery setting could produce the same height growth in lodgepole pine and Sitka spruce (*Picea sitchensis*) in 14 weeks that normally occurred in 16 weeks. Patterson and Flint (1982) showed that growth enhancement of soybean by high CO_2 (675 ppm) was greater with one-half strength Hoagland's solution than with one-eighth strength. This was true regardless of the fact that soybean is capable of symbiotic nitrogen fixation.

Brown and Higginbotham (1986) studied the combined effects of nutrient status and increased CO_2 on seedlings of white spruce and trembling aspen. In spruce, relative increases in total mass induced by high CO_2 were similar in high-nitrogen (N) and low-N (50%); absolute gains were greater in the high-N plants. In aspen, CO_2-enrichment caused early, temporary increases in biomass regardless of nutrient level. After 30 days this effect disappeared, likely because of nutrient supply problems.

Norby et al. (1986) reported a nutrient/CO_2 response that has been reported for nonwoody plants (e.g. Patterson and Flint 1982) and which may apply to northern tree species in some instances. White oak (Quercus alba) was grown for 40 weeks in nitrogen and phosphorous-deficient soil under enriched CO_2. Biomass increased by 85% even under these conditions, apparently as a result of decreased leaf senescence (greater leaf area duration) in high CO_2. They also point out that differential effects of CO_2 increase on nutrient uptake may occur between different nutrient elements.

A further factor related to nutrient availability under high CO_2 conditions is that higher leaf areas in early years of the life cycle, along with potentially greater leaf area duration in conifers, may mean a greater drain on soil nutrient reserves than normal. This problem could be exacerbated because carbon to nitrogen (C/N) ratios tend to decrease anyway under high CO_2 growing conditions. If the balance becomes too distorted, serious physiological consequences could result. These could include negative effects on enzyme processes and amino acid production which in turn could affect growth, photosynthesis, respiration, etc.

Greater requirements for nutrients when trees are growing in enriched CO_2 may also indicate increased importance of mycorrhizal associations which are important to expanding the effective root surface of the tree and which appear to increase the effectiveness of uptake of some nutrient elements such as phosphorous (Navratil 1981). However, Higginbotham (1987) reported that establishment of mycorrhizae is a process which is associated with high carbon use. White spruce and lodgepole pine seedlings were grown at normal (340) and high (600 ppm) CO_2. Some were inoculated with Laccaria laccata, a mycorrhizal fungus, and some (controls) were not. Biomass of control plants was increased significantly in high CO_2. The infected plants in both CO_2 regimes had similar weights which were even lower than control plants in low CO_2. The growth response of seedling trees to high CO_2 can, apparently be very strongly modified, by the presence of mycorrhizal symbionts.

2.3.4.5 Growth

Growth (change in height, diameter, biomass) probably would be affected by CO_2-induced climatic change if for no other reason than we have already seen that the physiological processes which affect growth are influenced by such factors as temperature and moisture. Growth requires two processes: cell division and cell enlargement. Measured growth is largely a function of the second factor. Both cell division and cell enlargement are influenced by temperature because enzyme catalyzation of metabolic processes is occurring. Cell enlargement is influenced both by temperature and water. Increases in cell size require, and are stimulated by turgor pressure, or the pressure potential in cells. If soil moisture is low, or if transpiration demand is very high (factors discussed earlier) cell size will be reduced (Salisbury and Ross 1978).

The relative effects of temperature and moisture on growth will depend on the extent of climatic change, the adaptability of given plant species to the change and when plants grow. Boyer (1970) and Kramer (1957), among others, have pointed out that tree species which live in hot, relatively dry climates usually grow mostly at night. Those living in cool, moist climates grow mostly in the day. Some species apparently grow most during periods when the difference between day and night temperature is relatively great (thermo-periodism) (Kramer 1957). Some trees apparently grow best under constant temperatures. Tinus (pers. comm.) showed that maximum early seedling growth of white spruce occurred at a constant temperature of 19°C. Best growth of lodgepole pine seedlings was at 25°C. How Tinus' study should be interpreted is not known in light of the fact that temperatures in the field are not constant.

Suggesting the absolute effects of CO_2-induced climatic change on growth of the four species discussed in this study is very difficult. All four have extensive ranges and presumably each population is well adapted to its mesoclimate. Significant genetic variation in adaptiveness to differences in environment undoubtedly occurs. Responses to temperature and moisture change are probably the critical factors to consider in estimating of growth effects within the three ecological zones of this study. The boundary between predominantly forest and the forest grassland transition is probably determined largely by moisture (Bird 1961). The boundary between predominantly forest and the forest-tundra transition is likely determined by growing season temperature and length of the frost-free period (Rowe 1972).

Although expected optimal, maximum and minimum conditions for black and white spruce, jack pine and trembling aspen are certain to vary based on location and genetic constitution of species populations, Table 2.3 shows some pertinent information, seen in the literature, relating to temperatures and moisture relationships for these species. Again,

Table 2.3 Temperature and Moisture Relationships for Selected Species and by Reference.

Species	Temperatures (°C)			
	Maximum	Minimum[a]	Optimum	References
White spruce	37	-5	20	Zasada (1971) Eis (1965)
Black spruce	37	-5	18-24	Krajina (1970)
Jack pine	--	-9	19-20	Dykstra (1974) Satterlund (1973)
Trembling aspen	--	--	--	--
		Soil Moisture		
White spruce		-16 bars	mesic	Watson et al. (1980) Lopushinsky (1981)
Black spruce	very wet	very dry	mesic	Fowells (1965)
Jack pine	hygric	sub-xeric	mesic	Watson et al. (1980) Smithers (1961)
Trembling aspen	sub-hygric	sub-xeric	mesic	Watson et al. (1980) Krajina (1970)

[a] Growing season.

Note: These are relationships for seedlings.

The Jack pine information has been extrapolated from Lodgepole pine results.

lodgepole pine data are extrapolated to jack pine.

Maini (1972) showed a very strong effect on height of mature trembling aspen of latitudinal change across these boundaries in Saskatchewan (Figure 2.7) which probably reflects the effects of moisture and temperature.

Cessation of growth in trees at the end of the growing season will probably not be directly affected by CO_2-induced climatic change because this is normally a photoperiodic response. However, development of cold hardiness and true dormancy may be delayed. As trees cease active shoot growth because of the photoperiod trigger, they attain slight cold hardiness. The first hard frost of autumn and subsequent cold nights initiate the state of deep dormancy which allows woody perennials to withstand temperatures as cold as liquid nitrogen (-196°C) (Weiser 1970).

2.3.4.6 Reproduction

Flower and seed production in trees are normally prompted by conditions which generate large quantities of carbohydrates. This allows vegetative requirements to be met and the excess is then available for reproductive growth. Increased CO_2, as discussed earlier, should provide additional carbohydrate through enhanced photosynthesis. Warmer temperatures in the range of 1 to 5°C should stimulate earlier flowering unless it is under very strong photoperiodic control. In coniferous trees, the control of flowering by photoperiod is normally fairly weak (Pharis 1974). Flowering in trembling aspen, at least, appears to be strongly affected by temperature (K. Higginbotham personal observation). Seed maturation will also be speeded up by higher

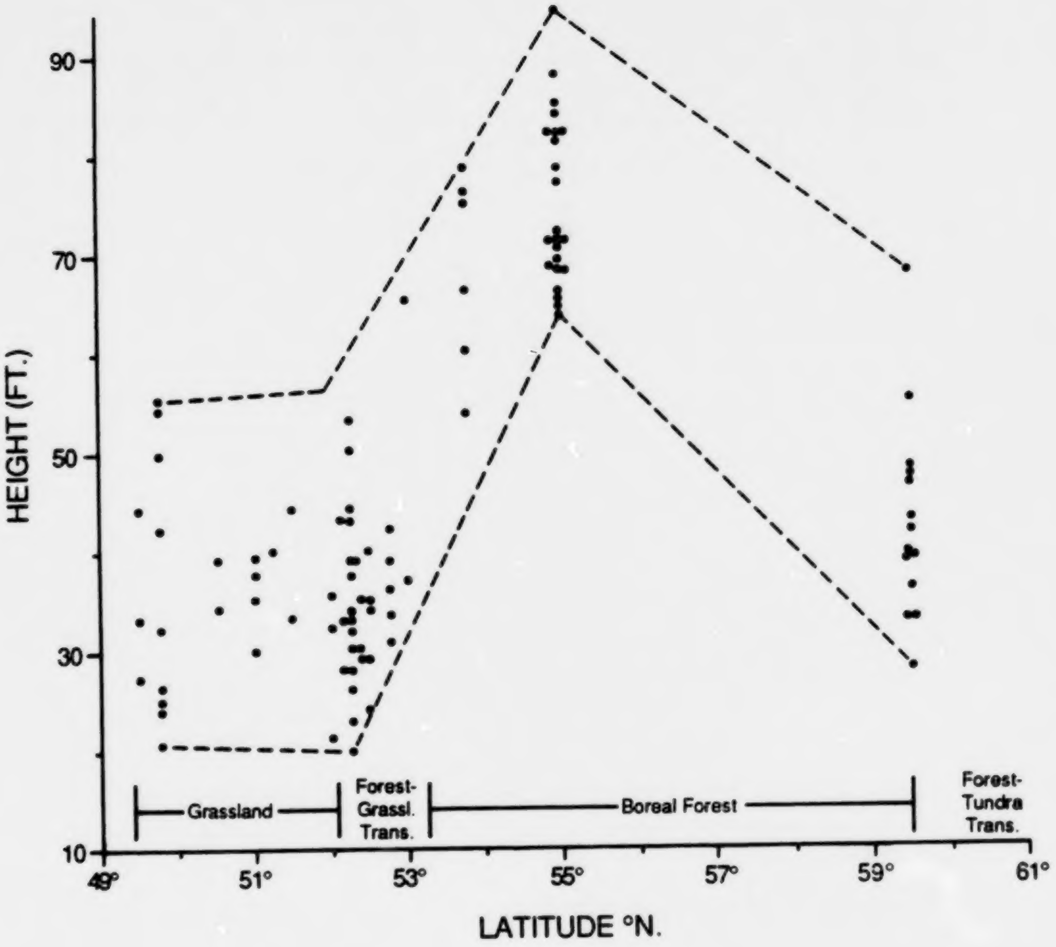

Figure 2.7 Influence of a Climatic Gradient on Height Growth of Trembling Aspen in Saskatcnewan (Maini 1972).

temperatures, which in the case of the boreal forest may be a positive factor (Clements 1966), because cool summers sometimes inhibit full embryo development.

Most successful regeneration of trembling aspen results from root suckering following death of the above-ground portion of the tree. While the major factor controlling suckering is a hormonal one (Schier 1973), soil temperature is also important. Maini and Horton (1966) showed that the number of suckers per unit length of root cutting and height of the suckers after 14 days both peaked at a soil temperature of 24°C. Soil temperatures below 18°C produced few suckers and very slow growth. Increases in soil temperature resulting from CO_2-enrichment will likely benefit the asexual reproductive process in aspen.

2.4 Forest Production in Relation to Climate

The above discussion has focused on the physiology of the individual tree in relation to climate. Trees grow together in stands. Stands are characterized by the mixture of various tree species of which they are made up, and by overall properties such as size distribution, basal area, wood volume, biomass, and productivity.

All stand-level properties are measured in relation to unit areas of land. The productivity of a stand, per unit area, is a summation of the growth rates of the trees of various species and sizes growing on that area. The trees do not grow in isolation, but rather compete with each other for resources - light, soil moisture, soil nutrients - of which there is a limited supply available on a unit area of land. Thus the productivity of the whole stand is limited by the same environmental factors as the growth of individual trees. Ultimately, the productivity of the stand depends on the rate of photosynthesis (and related processes) in the component trees.

A variety of measures are used to express the productivity of stands. "Net primary productivity" is the most complete measure, representing the total production of new plant material, but is the most difficult to determine. Foresters more often measure only part of this production: the growth of stem-wood volume, either the "current annual increment" (that is, the growth in a given year), or the "mean annual increment" (growth averaged over the length of the rotation). Finally, productivity is often expressed by "site index," which is based only on the rate of height-growth of dominant trees in the stand, and which is relatively easy to determine. All of these measures are correlated, but more complete measures give better expressions of the productivity of the stand.

Many studies relate forest productivity to climatic factors. On a world scale, net primary productivity rises with both temperature and precipitation (Lieth 1975). According to Bazilevich et al. (1971) and Drozdov (1971), moisture becomes the more important control in warmer climates, and heat more important in cooler climates. From the mid-boreal zone northward, according to their data, productivity actually declines with the wetness of the climate, because of the prevalence of saturated soils.

Studies focusing on the productivity of forests in the temperate and boreal zones have reached mixed conclusions regarding the relative importance of temperature and moisture. Downing and Weber (1984) found precipitation to be more consistently related to growth rates than temperature for a large data set of forests between 31° and 65°

latitude. Webb et al. (1983) found that the productivity of a set of United States forests depended mainly on temperature, but their data set did not include any forests from the drier climates. Gholz (1982) showed the importance of water balance for productivity of forests in the Pacific Northwest, where moisture conditions vary greatly.

In the boreal zone, it has usually been concluded that productivity is limited by temperature, not moisture (Peterson et al. 1983; Oechel and Lawrence 1985). In Finland, the geographic distribution of forest growth rates is well correlated with temperature accumulation in the growing season (Kauppi and Posch 1985), and the yearly variation in tree ring width is closely tied to seasonal temperatures, with precipitation having an effect only in the driest summers and on the driest sites (Mikola 1962). However, most of the evidence for the exclusive control of temperature seems to have come from the humid climate of northern Europe, or from studies on the subarctic fringe of the boreal forest (Oechel and Lawrence 1985). Most of the boreal forest in western Canada has a "dry subhumid" climate (Sanderson 1948), and the possibility of moisture stress as a limit on growth must be considered.

Studies comparing productivity performance in relation to climatic variables consist of two types:

1. Those relating spatial variation of climate to productivity.
2. Those relating temporal variation of climate to productivity.

The next two sections are organized by these types and selected references are chosen to illustrate examples of each study type. A review of some of the pertinent literature is found in Peterson et al. (1983).

2.4.1 Relationships of Spatial Variability in Climate to Productivity

Farr and Harris (1979) examined the relationship of site index in Sitka spruce to latitude and temperature. Stand locations ranged from southern Oregon to Alaska. In general, site index was highly correlated to both latitude and temperature (as expressed by mean annual growing degree-days). There were several outliers from the established regression, one of which has special significance in assessing the influence of future climatic change on productivity. On Kodiak and Afognak Islands the site index of Sitka spruce was much less than predicted. The Sitka spruce stands of these islands originated from the north where shorter and cooler growing seasons existed. It was hypothesized that because the stands were relatively new to the islands, they might not have been able to fully adapt to the local climatic potential. This research implies that there may be a considerable lag between climatic change and the response of forests (Solomon 1986).

Kauppi and Posch (1985) use the geographic variability in productivity and climatic variables to make inferences about the potential effects of climatic change on productivity. A linear relationship was found between tree growth (in m^3/ha/yr) and effective temperature sum (growing degree-days) using data from the whole of Finland. It is important to note that the activity of forest ecosystems in Finland is largely controlled by temperature, which may not be true in all boreal ecosystems. The relationship derived was then used to estimate the sensitivity of forests to possible climatic warming. In addition to the independent variables of temperature, the influence of continentality was also tested. A measure of continentality was obtained through assumptions of the variability in the temperature frequency distribution. Kauppi and Posch tested the effect of a 2°C increase in annual temperature on growth.

Given a constant degree of continentality, the largest relative increase in growth was shown to occur in northern (cold) regions. Similarly, for a constant temperature, the largest relative increase in growth was expected in maritime regions. The relative growth increases were considerable. For example, in a continental region with the average mean temperature of 0°C, a 50% increase in productivity was projected. It is cautioned that the growth responses may be overestimates because adaptation to a new climate takes time.

Viereck and Van Cleve (1983) relate a number of productivity and soil parameters to the summation of soil temperature degree-days using geographic variability in Alaska. Good relationships between degree-days and tree productivity, soil nitrogen, forest floor depth and a number of other variables were found. Predictions of vegetation change resulting from climatic change were made on the basis of these correlations.

The influence of genotype on the climate-productivity relationship should not be underestimated. Wright (1976) reports that the trend in growth rates (in Scots pine) with increasing latitude in northern Europe and Scandinavia is still maintained if the trees are tested in a common environment. From provenance testing, it has been found that trees in southern (warm) seedlots generally grow faster, leaf out later in the spring, grow later, and are less resistent to cold than trees in northern seedlots. Similarly, as compared with trees from a dry region, trees from a moist region generally grow faster, have smaller seeds, and are less deeply rooted (Wright 1976).

There are, however, many anomalies. Obviously, many of the observed trends are adaptations to the growing environment. However, it is difficult to determine if the adaptations are related to day length, seasonal temperatures, length of growing season, moisture, or other environment factors. The prediction of growth response due to climatic change is difficult given the uncertainty of present day adaptations. Even if a tree is able to adapt to increases in temperature, and thereby increase productivity, such adaption can take 10 or even 100 generations. However, introduction of other species into a warmer and perhaps more moist future environment might immediately realize the potential gain of a changed climate. Clark (1985) has indicated that, in agriculture, predictions of how present crops will respond to a changed climate are inappropriate because new crops that have been bred and selected for the changed environment will replace existing crops. The extent to which this occurs in forestry will, of course, depend on factors such as the rate of climatic change and the potential benefit of using growing stock with different genotype. If forest stands that are harvested or destroyed by fire are gradually replaced by growing stock that is able to utilize a more favorable growth environment, then the benefits for timber production can be realized immediately through the allowable cut effect (Clutter et al. 1983).

2.4.2 The Relationship of Temporal Variability in Climate to Productivity

Studies relating changes in climate over time to productivity avoid some of the problems common to studies using the spatial variability in climate. The growth response of the same genotype on the same site is assessed. In addition, any acclimation of the growth processes is incorporated in the growth response. There are many studies regarding the sensitivity of tree growth to temperature and moisture. Only a sample of the studies are discussed here.

Junttila and Heide (1981) related the shoot and needle growth in Scots pine of Northern Fennoscandia to temperature of the current and previous season. Shoot length and number of fascicles were positively correlated with the temperature of the previous growing season. Needle length was related to the temperature of the current growing season. Heide (1974) was also able to relate shoot growth to temperature conditions of the previous growing season (radial growth showed a significant but less pronounced effect). He found a wide temperature optimum for growth of 18 to 24°C for Norwegian ecotypes and a somewhat lower optimum of 15 to 18°C for a high altitude ecotype.

Mikola (1962) found that radial and height growth of Scots pine and Norway spruce was related to temperature of both the current and preceding growing season. As mentioned previously, temperature is often a limiting factor in forest growth in northern Europe and Scandinavia. Growth relationships with rainfall are generally only found in exceptionally dry summers. However, in most forests, 80% of the year-to-year fluctuation in diameter growth can be explained by variations in rainfall (Zahner 1968).

Skudra (1982) related current annual increment (CAI) in Scots pine and Norway spruce to six climatic variables in western Latvia. Temperature was found to be the most important factor for pine whereas the moisture regime of the previous season was more strongly related to CAI of spruce. Shrivastava (1982) also found that moisture regime strongly related to Norway spruce productivity as measured by height.

Guyon (1986) found that total annual height growth of Austrian pine was significantly correlated to cumulative rainfall in a portion of the previous growing season. In a more northern environment, Prokhorov et al. (1984) found that precipitation had no correlation with height growth; however, temperature was closely related to height growth.

The conclusion that can be drawn from these studies is that climatic variables do influence forest growth but that the effect varies substantially depending on geographic location. More specifically, it probably depends on the genotype which has adapted to a particular environment. Hence, extrapolation of results to different locations is likely to be difficult. In order to judge the sensitivity of existing stands in the Canadian boreal forest to climatic change, studies within these stands are required. Such information can be used not only to assess the influence of possible climatic change, but also to assess the assumptions regarding current yield forecasts which are based on past climate.

Dendrochronology and dendroclimatology use relationships derived between variation in climate and radial growth. These studies are frequently done in treeline environments (alpine or northern ecosystems) where temperature largely controls growth. The purpose is generally to identify climatic limitations on growth and thereby allow the reconstruction of past climates. The usefulness of these studies in assessing the growth of forests in the future is extremely limited. Most of the studies are done in extreme environments, unrepresentative of most forest conditions; the tree form is often very different than in most forests, and, finally, measurements of total growth are generally not done.

The use of detailed growth layer analysis, however, does show potential for the examination of climatic influences on tree growth and development responses (Fayle and MacIver 1985). A tree ring increment measuring (TRIM) system has been developed for precise measurement of tree rings and for growth layer analysis. Dendroclimatological and dendroecological studies can be supplemented by growth layer analysis.

Within Canada, there may be some indirect evidence of the relationship between growth and climate. Several studies have found that early height growth in forest stands has changed over time. For example, Dempster and Goudie (1984) found an inverse relationship between longevity and productivity of lodgepole pine in the boreal-foothills region of Alberta. Smith (1984) and Smith (1981) have also noted that older stands tend to have low site indices. It is possible that differences found in height growth over time are related to climate. A generally increasing temperature trend in the northern hemisphere has been noted by several researchers (Mitchell 1961; Jones et al. 1982; Jones et al. 1986; Singh and Powell 1986). However, other confounding influences, such as forest fire and stand density, could also be critical factors. Information about past stand conditions, stand dynamics and climate is insufficient to make any conclusions regarding the causative agent. Attempts at finding the causes of the relationship between site index and stand age may not be possible because of the inability to reconstruct past stand conditions and environment.

2.5 Possible Impacts of Climatic Change and CO_2-Enrichment on Structure and Function of Boreal Forest Ecosystems

Specific projection of ecosystem changes resulting from CO_2

increases in the boreal forest is reserved for Chapter 4. This section discusses theoretical ways in which processes and structure of forest ecosystems might be changed by direct effects of enriched CO_2, or by CO_2-induced climate change.

Any ecosystem includes all of the living organisms and the elements of the physical environment present at a particular place. However, the term implies much more than just an inventory of the component parts. Living organisms require resources which they obtain from geological or atmospheric elements of the system. Some organisms may be limited by availability of these resources. The living parts of the system interact in complex ways: predator-prey, symbiosis, mutualism, competition, etc. These interactions may cause reduced or increased access to necessary resources for different species. An ecosystem changes in structure and organization over time as a result of interactions between organisms, and as resources become more or less available. Various processes, such as decomposition of dead organic material and streamflow, act to preserve resources, and to add to them or sometimes to remove them from the system. These processes are very important to the long-term integrity of the system but also are involved in effecting change.

Because ecosystems are so complex, it is difficult to even make strong theoretical statements as to how CO_2-enrichment may affect them. However, a few ecosystem considerations of importance are discussed below.

2.5.1 Competition

One of the most important ways in which organisms interact in an ecosystem is through competition for resources in potentially short or limiting supply. No studies have yet been done in forest ecosystems on how these relationships may change under high CO_2. Bazzaz and Carlson (1984) and Zangert and Bazzaz (1984) studied competitive dynamics of assemblages of annual plants (communities) under various levels of CO_2. Total community production increased under enriched CO_2. The extent was affected by light intensity and moisture but not by nutrient availability in these studies. This finding tends to support the statement from Shugart and Emanuel (1985) that terrestrial ecosystems are not particularly CO_2-limited; the principal limiting factors tend to be water or nutrients or some other factor (such as light).

The percentage of total production contributed by each species in the studies mentioned above was strongly changed by CO_2-enrichment, meaning that some species respond more to the fertilization effect of CO_2 or climatic changes induced by CO_2 than others. In this way, the competitive relations between species are altered and the make-up both in terms of species present and numbers of individuals of each species is changed.

An example of where this finding could be of great importance might be where reed grass (*Calamagrostis canadensis*) and white spruce grow together. Dense grass tends to cause serious problems for the spruce. If spruce responds better to enriched CO_2 than the grass, the trees may gain an early advantage. If the grass is more successful, spruce mortality may increase.

2.5.2 Succession

Natural changes in species composition over time are called natural succession. Increased CO_2 tends to speed up the life cycle of most C_3 plants (Bazzaz no date). Opening of ecological niches for species which follow pioneer species on disturbed sites may occur much more quickly under CO_2-enrichment. Changes in competitive relationships may also change the current sequences or seral stages (Odum 1969) now found in successions.

2.5.3 Nutrient Cycling

Shortened life cycles should increase the rate at which nutrients tied up in woody perennials are added back to the forest floor and ultimately to the soil. Decomposition rates should accelerate due to warming of the forest floor. Temperature is very important to decomposition of organic matter and to release of mineral nutrients particularly in the boreal forest. However, litter quality (C/N, C/P ratios) may decrease, yielding reduced rates of decomposition. If warming of the forest floor is significant enough, the species of decomposing organisms involved in the process may also change. If the nutrient cycle is not constrained by cycling rate, forest sites will become more fertile (a greater percentage of the nutrient pool will be available annually) and the importance of mycorrhizal relationships could decrease.

2.5.4 Hydrology

The relative position of the water table to the surface of the forest floor is critical to ecosystem functioning. If precipitation and temperature increase, and result in a raised water table in a wet or wet-mesic area, one might expect some increase in anaerobic conditions which will affect species make-up and growth rates. Less precipitation could lead to water deficits in some areas, reduced growth rates and changes in community structure.

Streamflow may also increase in some instances with increased precipitation. This could change the current balance between nutrient inputs from other upstream systems, and the loss of nutrients to downstream systems.

2.5.5 Primary Production

Kramer (1981) stated that many assume that increased CO_2 will increase global photosynthesis and, therefore, increase biomass production in ecosystems. Availability of other resources, such as nutrients and water, which often limit current ecosystem productivity are important in determining whether primary production will really increase (Shugart and Emanuel 1985). Competitive and other interactions will also influence the availability of these resources to different species. Increased temperature will increase respiration and thereby influence the rate of carbon accumulation. In an extreme example, Billings et al. (1982) showed that an increase of 4°C in summer temperature caused increased respiration and lowered the water table enough in an Arctic tundra community to change the system from a net sink to a net source of atmospheric CO_2.

Prediction of changes in ecosystem productivity is made very difficult by the problem of "scaling up" from the measured responses of individual species to the ecosystem - an ecosystem is not simply the sum of its parts (Shugart and Emanuel 1985).

2.5.6 Herbivory

There is significant likelihood that the carbon/nitrogen and carbon/phosphorous ratios in plants will both increase as a result of the photosynthetic response to enhanced CO_2 (Strain and Bazzaz 1983). This will probably cause greater rates of herbivory. Lincoln et al. (1984) showed that soybean looper larvae ate 80% more when feeding on soybean leaves grown at 650 ppm CO_2 than on leaves grown at 350 ppm. Problems in the boreal forest, such as defoliation by spruce budworm or forest tent caterpillar and browsing by snowshoe hares, may increase significantly.

2.5.7 Environmental Pollution

Carlson and Bazzaz (1982) and Coyne and Bingham (1977) both report that high CO_2 ameliorates the effects of SO_2 pollution on photosynthesis. This finding probably relates to the partial stomatal closure of C_3 plants associated with enriched CO_2, and it may also have to do with increased growth shown by CO_2-enriched plants. Perhaps the amount of SO_2 per unit area or volume of plants is reduced through increased growth. Whatever the explanation, it appears that boreal forests (with C_3 vascular plants) will be more resistant to pollution by SO2 under conditions of an enhanced CO_2 atmosphere.

2.5.8 Summary

Solomon and West (1985) summarized the factors they felt were known, unknown and/or uncertain in order to resolve questions regarding ecosystem response to atmospheric CO_2 increases. Their table brings together many ideas, and also points out how complicated it is to understand reactions and interactions in these complex systems (Table 2.4).

2.6 Climatic Zonation of Forests

Another important aspect of the climatic influence on forests is the zonation of forest types, which reflects the relative competitive advantages of different species and different growth forms under various climates.

The North American boreal forest is a clearly definable biome, characterized by a few widespread species of spruce, fir, pine, larch, poplar, and birch. Transition zones occur northward with the arctic tundra, and southward with temperate deciduous forest in eastern North America. The general zonation from north to south under humid conditions is summarized in Table 2.5.

Temperature appears to be the dominant control on the distribution of the boreal forest, as the pattern of the above zones is strongly correlated with isolines of various thermal parameters (Table 2.1). Bryson (1966) showed that the northern and southern limits of the boreal forest match the average summer and winter positions, respectively, of the Arctic front, which separates cold and warm air masses.

However, moisture variation is also important. In the Prairie Provinces, the boreal forest grades southward into temperate grassland (over a transition zone of mixed forest and grassland called aspen parkland), apparently reflecting a shift from subhumid to semiarid climate (Coupland and Rowe 1969). A comparison of maps of forest distribution (Rowe 1972) with climatic maps (Environment Canada 1987) suggests that the balance between precipitation and temperature is

Table 2.4 Primary Knowns, Uncertainties, and Unknowns Requiring Resolution in Order to Appraise Forest Ecosystem Responses to Climatic Change Induced by CO_2.

Issues	Knowns	Uncertainties	Unknowns
A *Issues Detailed in Other SOA Reports*			
1 *Carbon Cycle Issues*			
a. Atmospheric CO_2 Accumulation	Atmospheric CO_2 concentration is rising	Preindustrial CO_2 value	Time when doubled and maximum CO_2 will occur Maximum future CO_2 concentration
	Seasonal CO_2 amplitude is increasing	Source of increasing amplitude	Significance of amplitude changes to carbon cycle, vegetation, climate effects
	Land use (forest clearance) contributes to atmospheric CO_2	Rates at which land-use generates atmospheric CO_2 increases	Future contribution to CO_2 by land use
b. Atmospheric CO_2 Depletion	Oceans are the primary global atmospheric CO_2 sink	Rates at which CO_2 crosses the ocean-atmospheric interface by geographic region	Internal circulation of oceans by geography that controls up and down welling of CO_2- rich and CO_2-poor water masses
	Terrestrial biota is a secondary global atmospheric CO_2 sink	Current areas and amounts of carbon stored in terrestrial biosphere	Future carbon source, sink, and storage properties of terrestrial biosphere
2. *Climate Effects Issues*			
a. Geography of Climate Change	Greater warming at poles than at equator	Intensity of latitudinal temperature differences	Local and regional temperature shifts
	Changes will occur in geography of precipitation	Geography of precipitation	Local and regional precipitation shifts
b. Variance from Mean Climate Changes	Variance may or may not change	Presence or absence of variance changes from current geography	Amount of variance change, if any, locally, regionally, globally
c. Temporal Chronology	Climate will change over time	Rate and nature (step function, climate continuous linear, etc.) of climate change	Temporal chronology of climate change
d. Seasonal Features of Climate Changes	Greater warming in winter than in summer	Amount of seasonal warming	Local and regional change in seasonal warming
	Quicker warming in summer than in winter	Time difference between summer and winter rates of warming	Local and regional time difference between summer and winter warming

Table 2.4 (Continued)

Issues	Knowns	Uncertainties	Unknowns
3. *Vegetation Effects Issues*			
a. Applicability of Single Factor Greenhouse Experiments to Multifactor Field Situations	Published reports on single-factor experiments show increased photosynthesis, decreased water use, increased leaf area, increased dry weight, increased photosynthesis in shade	No published reports on multiple factor experiments that realistically simulate field conditions; whether mature trees and ecosystems will respond similarly	Amount, if any, of response in multifactor situations; quantitative importance of offsetting (canceling) factors to tree growth
b. Applicability of Short Duration (hour, day) Fumigations to Long-Term Tree Growth	Published reports on longer term (months, seasons) experiments show short-duration effects decline and/or disappear	Will field-grown trees cease responding to CO_2 increases	How much, if at all, will field-grown trees acclimatize to enhanced CO_2
c. Applicability of Experiments on Herbaceous Annuals, Leaves, Branches, and Tree Seedlings to Mature Trees	Effects in 3a are found in these plants or plant parts	Will mature trees respond as do plants or plant parts tested; if so, what is the nature of forcing function (linear, logaritmic, etc.)	Amount, if any, by tree species or by other functional unit (shade tolerance, growth rate, etc.) that trees will respond as do other plants or plant parts
d. Applicability of Experiments in 3a, 3b, 3c, to Regional or Global Vegetation	The few trees and fewer species examined to date have declined in growth, while CO_2 has increased in concentration	Has the current 30% CO_2 increase affected tree growth; importance of climate change and other pollutants during same period in depressing tree growth.	Will future changes in climate and atmospheric pollutants negatively affect tree growth; if so, how much compared with possible CO_2 effects
B. *Issues Detailed in this Report*			
1. *Seedling Survival*	Temperature, precipitation variance control initial seedling survival	Will temperature and precipitation variance change in the future	By how much, if any, will variance in temperature and precipitation change
	CO_2 enhancement, below current forest floor concentrations, increases vigor, production, biomass, leaf area, and drought-tolerance differentially by species.	Will CO_2 enhancement above current forest floor concentrations have the same effects	Will CO_2 increase have long-term effects on massive mortality and, if so, which species will be favored
	Pathogens and predators destroy seeds and seedlings	Will pathogen and predator effects be different in the future	Which species will be favored and by how much if predator and pathogen effects occur
2. *Sapling and Tree Growth*	Climate variance controls geographic ranges of mature species	Specific climate variables and their variance values controlling the cold, warm, and dry parts of each species' geographic range	Future local and regional climate variances; future effects of CO_2 on responses of species to climate variance; future geographic range of species
	Climate variance controls annual growth rates	Specific climate variables and their variance values	Future local and regional climate variances; resultant shifts in competitive advantages among species
	Nutrients for growth depend on decomposition rates	Will decomposer populations change nutrients available because of warming of soils	Future amount of nutrients available because of changes in decomposer activities due to warming
	Root respiration depends on soil temperature, water, and oxygen availability	Will root respiration increase because of climate change	If root respiration changes, will it counteract increased production from CO_2 if such increases occur
3. *Death and Reproduction*			
a. Senescence	Senescent trees die from stresses that younger trees can survive	If climate changes continuously, will trees become prematurely senescent because of the additional stress of this continuous change	Will CO_2 induce vigor and prolong tree life and, if so, which species will be most affected and which will be least affected
b. Catastrophic Age-Independent Mortality	Wildfire frequency and intensity depends on climate, fuel, and time since last fire	Geographic change in wildfire frequency and intensity due to future climate change	Local, regional changes in the temperature and precipitation extremes that control fire frequency and intensity
	Windstorm and flood damage depends on frequency of rare climate extremes, topography, land-use	Geographic change in land use due to climate change	Local, regional distribution of future rare precipitation, wind extremes
	Pathogen, insect epidemics occur rarely	Climate dependency of pathogen, insect epidemics	Will climate control pathogen and insect epidemics and, if so, how

Table 2.4 (Continued)

Issues	Knowns	Uncertainties	Unknowns
c. Chronic Age-Independent Mortality	Occurs when production is too slow to provide enough fixed carbon for metabolism, slowing growth, reducing resistance to stress	Quantification of "too slow" by species of tree	Will CO_2 experiments with seedlings apply to mature trees, reducing chronic age-independent mortality; future local and regional distribution, frequency of climate variance that slows growth
	Chronic insect predation on trees is a normal stress that vigorous trees survive	Will chronic insect attacks change because of changing climate variance, changing forest composition	Climate variance that controls insect population sizes, species composition; forest composition that controls same
	Air pollutant damage (gaseous, acidic precipitation) is an increasing stress from which vigorous trees previously survived	Future air pollutant levels; loss of tree vigor by species to future air pollutant levels	Future combined effect of unknown air pollutant levels, climate extremes, insect, pathogen predation, and CO_2 effects on forest growth
d. Plant Succession	Rates, outcomes of succession under current constraints by climate variance, seed sources, disturbance frequencies, CO_2 concentrations	Will rates slow because of stress of possible continuous climate change; presence,intensity of forest-dieback and recovery	Will CO_2 enhance rates by relieving stress; future local and regional distribution of climate constraints (variance); future disturbance by wind, fire, flood
e. Plant Migration	Trees migrated 100–400m/y in the past 10,000–15,000 years	Future migration rates on a land-use dissected landscape; survival of seedlings of species ill-adapted to new conditions	Availability of seed sources with time; availability of empty niches; tree planting

Table 2.5 Boreal Zonation in Eastern Canada, and Climatic Correlates of Zonal Boundaries.

Zonation of the Boreal Forest

(after Atkinson 1981,
Bradley et al. 1982, Sjors 1963)

Zone	Vegetation	Boundary	annual net radiation	frost-free days	days with mean temp. >0°C	days with mean temp. >5°C	mean temp. of warmest month (or of July)	temp. sum (monthly, >5°C)	temp. sum (daily, >5°C)	temp. sum (daily, >42°F)	Thornthwaite potential evapo-transpiration	Holdridge bio-temperature
Arctic	tundra											
		tree species limit										
High Subarctic	shrub tundra	tree form line	15-20 kly (3)	90 (1)	120 (2)	100 (1)	11-12°C (1)	15 (1)	600 (4)		320 mm (1)	3.0°C (1)
	forest tundra	tree line										
Low Subarctic	lichen woodland	forest line	30 kly (3)		168 (2)		15°C (3)					
High Boreal	closed conifer forest	mixedwood forest line										
Mid Boreal	mixedwood and conifer forest											
Low Boreal	mixedwood and conifer forest	southern boreal limit	35-40 kly (3)			175 (1)	16-18°C (3)	42 (1)	1300 (4)	2200 (5)	510 mm (1,5)	
Boreal Temperate (Hemiboreal)	mixture of boreal and temperate spp.					205 (1)		48 (1)		3000 (5)	560 mm (1,5)	
Temperate	temperate deciduous forest											

Sources:
1. Tuhkanen 1980
2. Hare and Ritchie 1972
3. Hare and Thomas 1979
4. Kauppi and Posch 1985
5. Thorpe 1986

critical for the transition to grassland (see zonation model Section 3.4). Within the main boreal zone, there is also variation in species composition reflecting the gradient from moister to drier conditions from east to west (Sanderson 1948). Balsam fir, for example, is a dominant species in the eastern boreal forest, but becomes much less common in the drier and more fire-prone west (Halliday and Brown 1943).

Modelling the changes in the limits of the boreal zone under climatic warming is based on the relationships noted above between present zonation and thermal isolines. Modelling is discussed in Section 2.7.

2.7 Modelling the Effects of Climatic Change and Enriched CO_2 on Boreal Forest Ecosystems

Modelling of the direct and climatic change effects of CO_2-enrichment in boreal forest ecosystems is still in its infancy. This is, in large part, because relatively little is known about these systems, few climate stations are located in these areas and predictions of climatic change from general circulation models are very broad-scale at the present time. In actual fact, models describing ecosystem responses in other parts of the world are not very well developed either.

Models designed to describe the responses of ecosystems to enriched CO_2 may have several objectives. Often, different models are required to satisfy different objectives. The most common objectives are:

1. To describe changes in boundaries of ecological zones.

2. To predict changes in ecosystem functions such as natural succession or nutrient cycling.

3. To estimate productivity (growth and yield) under enriched CO_2.

2.7.1 Modelling Ecosystem Boundary Changes

Models that describe changes in ecosystem boundaries (sensitivity to climatic change) seem to be most common at present. Normally, these models utilize climatic change projections from general circulation models (GCM's) and then apply these climatic parameters which seem to be particularly relevant to controlling boundaries of important ecological zones. The best parameter to use would require some evaluation. Tuhkanen (1980) showed that length of the growing season, growing season temperature sum, and potential evapotranspiration work about equally well in delimiting the boreal zones in Fennoscandia; potential evapotranspiration appears to give the best fit of these Fennoscandian zones to Canadian zonation. Modelling of the southern boundary of the boreal zone in western Canada is similar in principle, but must be based on both temperature and precipitation effects. A simple example of such a model is given in the Section 3.4.

Kauppi and Posch (1985) stated that temperature is very important to controlling the location of the boreal forest in Finland. They calculated effective temperature sums (essentially growing degree-days) for current boreal systems in Finland and then recalculated them based on atmospheric warming projections from the GISS GCM and suggested effects within the country. They defined the boreal zone as lying between 1,300 and 600 degree-days above 5°C. Climatic warming simulated from doubling of atmospheric CO_2 produced a northward displacement of this zone of 500 to 1000 km.

Holdridge's (1964) system uses a similar approach, separating the major types of world vegetation on a grid created by levels of annual precipitation and "biotemperature" (the average of monthly temperatures, setting those below 0°C and above 30°C to zero). Emmanuel et al. (1985a) modelled the change in distribution of Holdridge's vegetation types, which would result from doubling of atmospheric CO_2, by adding the projected temperature increases to the biotemperature. This model predicted great changes, with the boreal forest essentially replaced by temperate grassland and temperate forest. However, the method of calculation in this model exaggerated the changes to be expected (Rowntree 1985); recalculation resulted in more modest changes, but still resulted in a 37% reduction in boreal forest and 32% reduction in arctic tundra (Emmanuel et al. 1985b).

A more complex approach to climatic modelling of vegetation types is that of Box (1981). The distributions of the various plant growth forms (e.g. needle-leaf evergreen trees, broad-leaf deciduous trees) are defined by the upper and lower limits of various climatic variables. The vegetation of a given location is predicted to be dominated by the tallest of the plant growth forms that could grow there on the basis of its climate. This model appears to be too generalized for accurate predictions of changes in zonation in this study area.

Solomon et al. (1984) used some of the capability of the FORET growth and yield model (West and Solomon 1984) to predict major shifts in vegetation zones with particular focus on eastern North America. Few points were considered west of central Ontario. Most of the boreal forest considered in their study should probably be considered as wet boreal forest. They also considered forest tundra and temperate forest boundaries. They suggested that quadrupling CO_2 would be required to produce enough warming for tree growth to occur at Baker Lake, 350 km north of the present boundary. Doubling of CO_2 would allow closed forest to replace open parkland at Churchill and Shefferville. Deciduous species would not be present, however. They predicted that in the current predominantly forest area, white spruce and paper birch will become much more important. In currently warmer areas (near or south of Kapuskasing) white spruce would decline in importance.

These two examples indicate the wide variation in predictions which occur. In part, these variations depend on modelling techniques and model construction, and, in part, they depend on variation in GCM predictions used to fuel the ecosystem predictions.

2.7.2 Modelling Changes in Structure and Function of Ecosystems

The capacity (mathematical and computational) to model functional relationships in forest ecosystems exists, but building usable models is constrained by lack of data from studies which might quantify these relationships for ecosystems in boreal environments. The reason for this, of course, is the great amount of time, manpower and money necessary to adequately work out the complex relationships which exist in forest ecosystems. Botkin et al. (1972) developed the most well-known forest model of this type. JABOWA is based on many years of work on many aspects of the northern hardwood forest ecosystem at Hubbard Brook, New Hampshire. It has been suggested that this model has some applicability to boreal forests (Borman and Likens 1979). Stelter (1985) adapted the growth elements to some boreal tree species.

Models which predict single functional elements of forest systems are more common than those which predict multiple processes and their interactions. Successional models are probably the most common of this type. Shugart and West (1980) reviewed some of the elements of these.

Bartos (1978) developed what appears to be a very successful model for simulation of succession in trembling aspen ecosystems of the central Rocky Mountain region of the United States.

2.7.3 Productivity Models for Estimating CO_2-Enrichment Effects

Several models of the type already described include some estimate of productivity. Usually the estimate is of biomass change for a particular ecosystem type based on the effect of warming. These estimates appear to range from 30 to 85% increases in system productivity under doubled CO_2, but are usually based on very limited data.

Only two existing models have been specifically developed to deal with plant growth under long term CO_2-enrichment, namely FORET (West and Solomon 1984) and ARTUS-CO_2 (Oechel and Strain 1985). FORET is a stand growth model in which production is increased by preset amounts. The model then predicts changes in stand composition, growth rates and productivity. It is limited by a lack of field data and by the fact that most of the data which do exist are from short-term observations. Most data sources are also from studies where seedlings have been measured and extrapolation to mature trees is tenuous. The model assumes no changes caused by interacting factors such as nutrient cycling or increases in water use efficiency. Its best use is probably to evaluate "what if" scenarios rather than to be thought of as capable of definitive predictions.

ARTUS-CO_2 appears to predict effects of elevated CO_2 on the production of arctic plants quite well. It focuses on individual species and currently does not consider changes in vegetative reproduction, an important factor in arctic systems. The model increases photosynthesis as a function of increasing CO_2. It can react to a build-up of photosynthetic products. Effects on soil respiration can also be simulated. The authors see the model as a "codification" of current understanding of CO_2 effects on ecosystem functions and stress that more experimentation and validation are needed.

Another model, the simulator of northern ecosystems (SNECS) (Miller et al. 1983), was designed to predict changes in productivity and decomposition resulting from temperature change and CO_2. Its level of operation is several decades so its resolution is more like that of FORET than ARTUS-CO_2. It predicts carbon build-up or loss of systems rather than productivity of species. For example, it predicts increases in carbon sequestering for arctic and boreal environments of 2 to 8 times with a doubling of CO_2.

2.7.4 Forest Production Models for Estimating Climatic Effects

A wide variety of models, from the simplest to the most complex, have been used to predict the productivity of forests using climatic data. Appendix B gives more detailed notes on evaluating the usefulness of various models for the purposes of this project.

The simplest approach is regression of measured forest productivity at a variety of locations on climatic variables. Productivity data can be total net primary productivity from ecosystem studies (most of these were part of the International Biological Programme), or simply growth in wood volume from forest inventories. Climatic variables can be simple meteorological records, or any of the great variety of indices developed to express the accumulation of temperature, or the balance of moisture resulting from precipitation input and evaporative loss (Tuhkanen 1980).

Lieth (1975a) established generalized regressions of net primary productivity (from stations around the world) on mean annual temperature and annual precipitation. His "Miami Model" predicts net primary productivity as the lesser of the two predictions from the temperature and precipitation regressions, based on the idea of the law of the minimum. This model was used to predict the effects on regional productivity of climatic change; not surprisingly, changes in temperature had the biggest effect at high latitudes, and changes in precipitation at low latitudes (Lieth 1975b). Pittock and Nix (1986) used the same model to predict the change in net primary productivity in Australia under increasing CO_2.

Lieth's regressions have considerable dispersion of data points about them. Downing and Weber (1984) showed that this dispersion could be reduced by including stand variables such as biomass and age as predictors, along with the climatic variables. Their model predicted the growth of forests between 31° and 65° North and South latitude, with coefficients of determination between 0.6 and 0.8.

These models are highly generalized. Prediction can also be improved by restricting the geographic area. For stations across Finland, Kauppi and Posch (1985) calculated a closely-fitting regression of annual wood production against a growing season temperature sum. They also presented a method for calculating the temperature sum from simulated mean annual temperatures, and used this to predict the change in production under climatic change.

This simple approach seems readily applicable to assessing the effect of climatic change on forest production in western Canada. This method requires forest productivity data, most of which could probably be obtained from national inventory statistics (Bickerstaff et al. 1981; Bonnor 1982, 1985) and climatic data in order to develop the regressions. Testing of moisture, as well as temperature effects, is desirable, as suggested earlier. A further refinement is to account for variations in site (e.g. soil and topography) and stand characteristics (e.g. age) which complicate the relationship of growth to climate (Lemieux 1961).

Another simple, regression-based approach is represented by dendrochronological techniques that have been developed to estimate past climatic change (Fritts 1976). Tree ring widths are related to yearly weather variations over a recent calibration period, and the relationships are then used to estimate past weather from older rings. It may be possible to use such relationships to predict future ring widths from simulated future weather. The maximum wood density per annual ring may also be usefully related to weather variation (Jozsa et al. 1984). However, it is not yet clear whether climate/ring width relationships can be developed for boreal forest sites.

Somewhat different from these simple regressions on climatic variables is the use of complex climatic indices which have been found to be related to productivity. Usually these are multiplicative functions of terms related to radiation, temperature and moisture availability.

Lemieux (1961) evaluated the use of Paterson's CVP index, which had been developed to predict Swedish forest production, in forests of eastern Canada. It gives reasonable predictions related to growth and to forest zonation, but the use of precipitation as a multiplicative term produces excessively high values of this index for cool, wet stations.

Turc and Lecerf's (1972) climatic index of agricultural potential, CA, was developed in France, but has been correlated with productivity data around the world and also appears to be more sophisticated than Paterson's index. It consists of two terms: a dryness factor based on monthly soil water balance calculations, and a heliothermic factor based on monthly radiation and temperature. Williams (1985) used Turc and Lecerf's index to model the effects of climatic change on productivity across Alberta. Because this index includes both temperature and moisture terms, it made the reasonable prediction that warming without change in precipitation would reduce productivity in semiarid southern Alberta, but increase it in the north. It would be useful to calculate Turc and Lecerf's index for the present study area, before and after climatic change. However, any such index should be tested against real forest productivity data in the study area before drawing conclusions from it.

The next step up in complexity consists of models which attempt, in varying degrees, to model the production process mechanistically. Full mechanistic modelling of physiological processes is possible: Reed et al. (1976) modelled photosynthesis in tulip-tree (Liriodendron tulipifera) using radiation, temperature, CO_2 concentration and stomatal resistance as variables. But such models are species-specific and require environmental data at fine time-intervals. According to Dale et al. (1985), inclusion of better physiological modelling in forest growth models would raise computational costs excessively. Moreover, while modelling of photosynthesis has received considerable attention, much less is known about allocation of photosynthetic products in the plant to maintenance respiration, shoot growth and root growth (Running 1982). Therefore, a variety of intermediate approaches, combining empirical and mechanistic modelling, have more promise for forest growth predictions.

Emmingham and Waring (1977) presented a relative index of photosynthesis based on physiological information for Douglas fir. Only net photosynthesis is modelled, but the resulting index has been shown to be very well correlated with productivity of forest stands. Although it was developed for Douglas fir, it has been applied to a wide variety of ecosystems by Emmingham (1982). The model consists of multiplicative terms for the response of photosynthesis to light, the response to temperature, and stomatal conductance. Moisture stress, cold soils and frost are modelled as reducing stomatal conductance. Night respiration, as affected by temperature, is subtracted. The model requires daily data for air and soil temperature, shortwave radiation and xylem water potential (a measure of water content in the plant), so is not suitable in its present form for our purposes. However, Running (1982) suggested a modelling strategy based on this index, but modified to run on data extrapolated from meteorological stations.

In models which attempt to model growth of trees, and not just photosynthesis, a widely-used approximation is to model growth as increasing with leaf area (the source of photosynthesis), but decreasing with total biomass (i.e. with respiratory demand). Webb et al. (1983) used a term of this sort (but also dependent on radiation and temperature) in a simple regression of measured net primary productivity of United States forest sites.

The large family of forest growth models descended from JABOWA (Botkin et al. 1973) uses this approach to model the growth of individual trees. In these models, the trees on an array of small subplots are born, grow, and die over several centuries to simulate the patterns of long-term succession. The growth rate of each tree is based first on an optimal growth curve for the species, with leaf area and total biomass as independent variables, as noted above. The parameters of this optimal growth curve are determined simplistically from the highest reported diameters, heights and ages in the literature. Limitations to growth are then modelled as multiplicative terms with values from zero to one; these can include reduced light due to the shade of other trees, suboptimal temperatures, moisture stress, or other factors. The temperature factor is again modelled simplistically, using the temperature sum in the growing season. Each species is considered to have a growth response of zero at the temperature sum found at its northern and southern range limits, while the response between those limits forms a parabola with a maximum value of one. In recent versions of the model, moisture stress is modelled as a limiting factor based on soil water balance calculations.

The temperature dependence of growth in this type of model was used by Solomon et al. (1981) to simulate the changes in forest composition in Tennessee during post-glacial warming; for example, the transition from boreal forest to temperate deciduous forest in the simulated output resembled the transition indicated by pollen records. Botkin et al. (1973) also used their model to simulate the fertilizing effect of an increase in atmospheric CO_2, simply by increasing the simulated diameter growth of each tree in each year by a constant percentage.

Models of this family have been found to be readily transplanted to different forest regions, because they depend only on simple silvicultural information for each of the tree species, and standard weather data (Dale et al. 1985). Solomon (1986) has already applied a model of this type (FORENA) to arctic and boreal stations in eastern Canada, and used it to predict changes following climatic warming. This is probably the best model available for predicting changes in species composition through several generations of forests. However, its accuracy is questionable because of the simplistic assumptions regarding optimum growth patterns and the response of growth to temperature. Even the modelling of the present forests under present climate by Solomon (1986) makes the wrong species dominant in the boreal stations. The accuracy of the prediction of forest growth rates is unknown.

Reed (1980) produced a more sophisticated version of this type of model for Douglas fir forests using more empirically-based functions for optimum growth and the effect of limiting factors. His model is also more efficient in that it grows cohorts of same-aged trees, rather than individual trees. Unfortunately, the resulting model is too stand-specific to be applied generally (Downing and Weber 1984), and has excessive data requirements for our purposes. Kimmins' (1986) FORCYTE model also has a good empirical base for yield predictions, as it is structured around empirical yield tables, modified by simulations of the effects of light and nutrient supply. But it is even more stand-specific, accepting climate as a given, and thus cannot be used in its present form to model changes due to climatic variation.

The most ambitious and complex model found is the Northern Ecosystems Carbon Simulator of Miller et al. (1983). Their intent was to model the carbon flux of the entire boreal and polar region by modelling plant production and other processes for each of the major vegetation zones. In spite of this broad scale, their approach is very physiological, with explicit models for photosynthesis, respiration, and growth, on an average basis for each zone. This allowed them to simulate the fertilizing effect of increasing atmospheric CO_2, which is assumed to cause a directly proportional increase in photosynthesis. Suboptimal temperatures are modelled as limiting both photosynthesis and growth.

A valuable feature of this model is the importance attached to soil processes. Nitrogen and phosphorus supply from the soil are treated as limiting factors; the realized growth rate is the least of the rates allowed by carbohydrate supply (from net photosynthesis), nitrogen supply, or phosphorus supply. Decomposition rates depend on temperature, so that climatic warming increases growth partly by accelerating decomposition and thus increasing nitrogen supply. Thawing of permafrost is also simulated. While this model has many interesting features, it is evident from its scale that it must have a great number of parameters, many of which are estimated arbitrarily. Inaccuracy in the present formulation is suggested by the fact that the model predicts higher productivity in the mid-boreal forest than in the southern boreal, contrary to known patterns. It seems unlikely that the parameters in such a far-ranging model can be estimated accurately with present knowledge.

In conclusion, the simple, empirical models based on present productivity and the present climate have obvious relevance and should be the first step in developing predictions of productivity under changing climate. A preliminary example is presented in a later section. But these simple models have limited capacity for simulating the pattern of forest growth over a rotation, or for incorporating complicating factors such as the direct fertilizing effect of increasing atmospheric CO_2. Unfortunately, none of the more complex models reviewed is suitable in present form for the goals of our study. FORENA and the Northern Ecosystems Carbon Simulator have been applied to the boreal forest, but their results are questionable, as discussed above.

In the ideal model for our purposes, it would be desirable to have a model of photosynthesis, as this would allow the application of the fertilizing effect of CO_2. Probably the simple approach of Emmingham and Waring (1977) offers most promise, using physiological information available for boreal species, and modified to run on standard meteorological data as suggested by Running (1982). However, it is not clear whether such a model can be used to simulate growth accurately, because of uncertainty about the allocation process in the plant.

The general biomass production model developed for the Food and Agriculture Organization by de Wit (1965) has been used to estimate Canadian forest production by Agriculture Canada (Clark, no date). It incorporates a photosynthesis model, and is driven by climatic and general soil variables. Predictions have been mapped at a national scale. The correspondence between the model's estimated potential productivity and measured forest productivity (CLI) is good on the better drained sites. Improvements to account for soil drainage, and possibly exposure were reported to be underway. The model has been used in a previous climatic change study to estimate wheat yields (Williams et al. 1987). Thus, this model appears promising for further work in assessing climatic change impacts on forest production.

Probably the most practical approach to growth modelling for our purposes would be based on an optimum growth function with strong empirical content based on such information as site index curves (Reed 1980) or yield tables (Kimmins 1986) modified by limiting factors. These should include temperature (especially the effect of insufficient heat accumulation in the growing season), moisture (based on soil moisture balance calculations) and nutrient supply (based on decomposition processes). It should be formulated to require only standard meteorological data. Such a model could be built largely from components borrowed from the models reviewed above.

2.7.5 Growth and Yield Models

Growth and yield models used in forest management planning are normally mensurational in nature and do not have environmental components, and seldom have capability for calculation of productivity. However, a few models are now in use which, with appropriate modification and validation, might account for the direct and indirect effects of CO_2-enrichment on yield and which could still be used for management decision-making. These models all have ecological and/or biological inputs. No attempt is made here to rank the models in terms of current quality, difficulty of renovation, type of model, or data necessary to use the model. They are simply listed by name, author and species.

Model Name	Authors	Species
Prognosis	Wycoff et al. 1982	Intermountain conifers
FORET	West and Solomon 1984	Eastern hardwoods
JABOWA	Botkin et al. 1972	Northern hardwoods
FOREST	Ek and Monserud 1979	Mixed conifers, aspen
TASS	Mitchell 1975	Douglas-fir, lodgepole pine and being developed for white spruce
FORCYTE	Kimmins and Scoullar 1983	Douglas-fir, coastal conifers

2.8 Climatic Change Effects on Forest Fires

Forest fire activity depends mainly on short-term weather usually of no more than several days duration (e.g. Van Wagner 1985; McLean and Coulcher 1968; Brotak 1982; Alexander et al. 1983). As Van Wagner (1985) indicates, the relationship of long-term weather to fire behaviour is poor and is of minor importance in comparison to short-term conditions.

It is the frequency of occurrence of the short-term weather conditions associated with major forest fires that will largely control the nature and extent of fire in the future. Consequently, estimates of the changes in climatic normals over time are somewhat meaningless in predicting future forest fire behaviour. It is possible to add the predicted increase in average temperature to past temperature records and then calculate an average Fire Weather Index (for description see Van Wagner 1974) in much the same manner as Simard (1973) has done. This approach was used to estimate an effect on a drought index in Saskatchewan (Williams et al. 1987). However, such an approach assumes that the frequency of extreme weather remains the same as in the past, and that the average increase in temperature occurs uniformly across all weather patterns. The utility of this exercise is limited since circulation patterns and storm belts are expected to shift poleward, which will likely change the nature and frequency of extreme weather patterns. Variations in seasonal precipitation rates and temperature have been projected to increase (Woodman 1984). However, estimates of the change in the frequency of extreme events have not been established.

Parry and Carter (1985) discuss the notion that economic and social systems adjust to climate change by responding to changes in the frequency of extreme events, rather than to the long-term change of average conditions. It is certainly true in forestry that extreme events result in management changes. For example, Murphy (1985) outlines how particularly severe fire years have resulted in changes in fire management policies. If there is an increase in weather events which significantly increase forest fire occurrence, the priorities of forest management would rapidly change in response. Changes in forest fire activity have the potential for substantial alteration of species composition and forest structure. It is possible that changes in the frequency of weather patterns affecting forest fire could overwhelm any changes in forest productivity due to climate or CO_2-enhancement. However, projections of the changes in extreme weather frequency are not currently available.

Significant changes in the fuel complex related to increases in atmospheric CO_2 may occur. For example, Higginbotham et al. (1985) showed that secondary leaf biomass of lodgepole pine seedlings more than doubled when grown under a 3 x CO_2 environment. There is, of course, a great deal of uncertainty regarding the response of mature and immature trees in natural stand conditions. Leaf biomass is important in fire behaviour because the principal fuel consumed in crown fires is live foliage (Van Wagner 1977). An increase in biomass within the crown would result in a corresponding increase in crown bulk density. Crown bulk density has been shown to be a very important factor in determining the rate of spread in crown fires (Van Wagner 1977).

Another morphological effect of enhanced CO_2 concentrations is an increase in branching of both woody and herbaceous plants (Woodwell 1983; Kramer 1981). Depending upon the form of the tree, crown bulk density could increase as a result of the change in branching habit.

The leaf-litter layer portion of the fuel complex may also change as a result of warmer climate because of increased decomposition rates (Viereck and Van Cleve 1983). However, if the duff layer should change, forest fire behaviour is unlikely to be significantly affected because the duff layer is largely unavailable as fuel for the main fire front. The duff layer does not contribute strongly to fire intensity or area burned (Van Wagner 1977, 1983).

Predictions of changes in the fuel complex due largely to the consequences of enhanced CO_2 concentration are extremely tenuous. The uncertainty regarding the response of plants and trees to CO_2 is the primary cause. For example, the response of species to enhanced CO_2 varies widely and the largest response is in seedlings. The response of older plants decreases or ceases with age (Kramer 1981) but, unfortunately, most research has concentrated on the seedling response.

2.9 Climatic Change Effects on Forest Insects and Diseases

Climate has an important bearing on the abundance, activity and distribution of both insects and disease. Whether climatic change will increase or decrease insect and disease dynamics and occurrence will depend on the specific hazards themselves. A few examples follow here to indicate how predicted climatic change might affect insects and disease.

The outbreaks of mountain pine beetle are strongly related to climate. Outbreak hazard maps such as those developed by Safranyik et al. (1974) depend largely on climate. Areas of high hazard are hot and dry with mild winters. In general, hazard increases with decreasing latitude, although topographic features do influence local climate thereby affecting hazard. Temperature is the most important climatic factor controlling beetle populations (Safranyik 1981). The poleward shift in isotherms which is predicted as a consequence of enhanced atmospheric CO_2 can be expected to extend the geographic distribution of mountain pine beetle. The increases in predicted temperature due to CO_2 are expected to be relatively greater in the winter months (Introduction and Section 4.1.1). The mild winters will probably favour mountain pine beetle; larvae of bark beetles are generally killed in extremely cold winters (Furness and Carolin 1977).

Areas currently within mountain pine beetle range can be expected to have higher hazard ratings. Safranyik et al. (1974) and Safranyik (1981) indicate that hazard is related to the expected frequency of periods favorable for an increase in beetle population and, to a lesser extent, inversely related to adverse weather conditions such as cold winters. Changes in global circulation patterns are very likely to change the frequency of favorable and unfavorable weather patterns; however, the resolution of current general circulation models is not sufficient to predict such changes.

Population dynamics of spruce budworm are also influenced by climate. Ives (1974) found that population changes were related to temperatures in winter and in the period following the third instar. Most expansions of infestations were observed to occur during relatively dry years. Wellington et al. (1950) and Greenbank (1956) also support the notion of a fairly strong correlation between spruce beetle populations and weather. However, Royama (1978) believes that the survival of large budworm larvae is relatively insensitive to weather conditions. He relates outbreaks to a perturbation of an endemic equilibrium state, but concedes that the perturbation may be weather induced. Regardless of the mechanism, it does appear that there is general consensus that weather conditions affect spruce budworm populations.

Climate is important in determining the activity of pathogens by regulating spore production and mycelial growth (Smith 1970). Weather and climatic variability are also capable of influencing host susceptibility by weakening or predisposing them to pathogens or insects. In Idaho, Beard et al. (1983) found that stalactiform blister rust was restricted in elevational and latitudinal range by temperature. He also found that incidence of the rust decreased as moisture increased, irrespective of temperature. Van Arsdel et al. (1961) found that the spread of white pine blister rust was influenced by temperature and moisture conditions. The infection of pine required at least 48 hours with saturated air at less than 68°F (20°C). This is one example which illustrates that an increase in temperature may not always be deleterious to tree health. Thomas et al. (1960) found that levels of fungi infection in aspen and balsam poplar varied depending on site moisture regime, although the reasons underlying the differences in infection levels were not investigated. Climate can obviously affect the moisture regime and thereby may influence fungal activity.

2.10 A Review of Methods Used to Estimate Economic Benefits of Climatic Change

In this section, we review the literature on measuring the economic benefits and costs of climatic change. Much of this literature considers the economic effects of changing climate on agriculture, but we are interested in the methodology, not the particular application. We begin by examining the concept of benefits as opposed to impacts. Then we investigate the methods employed by others, criticizing these where we feel the methodology is inappropriate or misleading. Finally, we suggest a correct approach which is pursued in greater detail in the following sections.

While scientists have been unable to determine the exact nature of the climatic changes, a number of studies have been conducted to determine the impacts of a changing climate under various scenarios (Parry et al. 1987; Kates et al. 1985). The studies examined the impact of climatic changes on agricultural output, on fish stocks and on the output of forests (Parry et al. 1987; Kates et al. 1985; Powell 1980). Economic impacts were analyzed in agriculture, and the procedure was to use linear programming (farm models) to determine changes in the mix of agricultural outputs and then to estimate the economic impacts using input-output models (e.g. Arthur et al. 1986; Parry et al. 1987; Williams et al. 1987). However, as Lovell and Smith (1985) indicate, input-output analysis looks at pecuniary benefits, or income transfers, rather than true economic benefits. Most studies of climatic change emphasize physical output. Where attempts are made to estimate the economic benefits, benefits are either left undefined or appear to be erroneously calculated, possibly because many of the economic studies were not conducted by experienced economists.

2.10.1 The Concept of Economic Benefits as Opposed to Socio-economic Impacts

In order to study the economics of climatic change, it is necessary to employ techniques developed in applied welfare economics, which forms the theoretical foundation of benefit-cost (B-C) analysis (Boadway 1974; Boadway and Bruce 1984; Diewert 1983; Just et al. 1982). In this literature, economic benefits refer to surplus areas either below the demand function and above price or above the supply function and below price. These concepts are known as consumer surplus and producer surplus (or rent), respectively.[1] In Figure 2.8, the equilibrium price is P^e. The consumer surplus at this price is given by area ($P^e bc$), while the producer surplus is measured by area (abP^e).

It is also important to distinguish between indirect economic "benefits" and indirect economic "effects." In the B-C literature, the concept of indirect benefits is well-established (Harberger 1971); but, in practice, there is much confusion between indirect effects and indirect benefits. Indirect effects, or secondary effects, are often erroneously referred to as secondary economic benefits by regional analysts and planners. They are also referred to as socio-economic impacts and these cannot be compared with economic benefits, although calculation of economic impacts may be useful to the authority in making decisions regarding the extent of income transfers between regions.

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[1] Consumer surplus is actually an approximation to one of the two true measures of the welfare of a consumer, namely, compensating variation or equivalent variation (Boadway and Bruce 1984; Just et al. 1982).

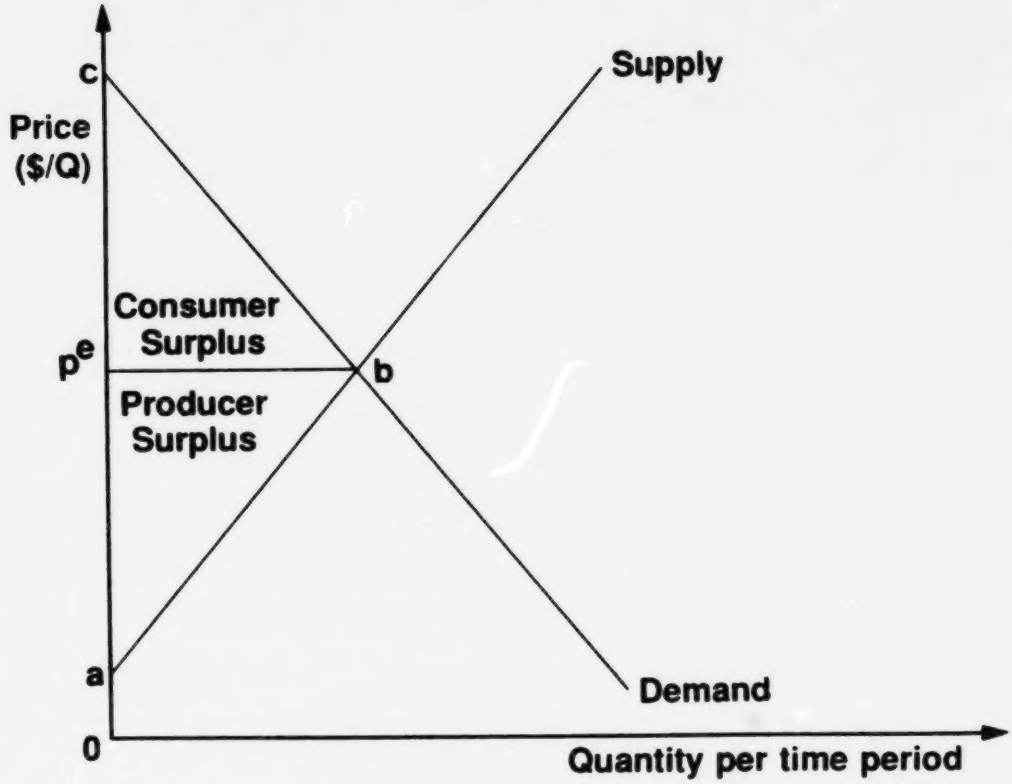
c
Price
($/Q)
Supply
Consumer
Surplus
p^e
b
Producer
Surplus
a
Demand
0
Quantity per time period

Figure 2.8 Concepts of Consumer and Producer Surplus.

Since indirect effects or impacts deal with pecuniary external economies or income distributional issues, they are not eligible as benefits in evaluating projects via benefit-cost analysis, or in determining the net economic benefits resulting from changes in climate.

Indirect benefits, on the other hand, are appropriate to include in the estimation of the economic benefits of a change in climate, but only in certain circumstances. Indirect benefits are measured when welfare impacts are to be calculated in a general rather than a partial equilibrium framework. What distinguishes the general from the partial framework is that the former takes into account welfare impacts in markets that are only indirectly affected by climatic change. For example, climatic change may increase the supply of timber products to firms producing paper products and/or it may increase the demand for logging equipment such as trucks. Indirect net economic benefits may be measured in these markets. However, welfare impacts in the affected forward and backward markets, or horizontal markets, are to be measured only when there are economic distortions (e.g. monopoly) in these impacted markets (Harberger 1972:48; Just et al. 1982:459).[2]

The net economic benefits of a change in climate which affects the growth of forests are equal to the value of the change in timber volume, plus the increase or decrease in welfare measured in related, but distorted, forward- and backward-linked and horizontal markets as a result of an increase or decrease in economic activity in the forest sector. The latter welfare effects are the indirect economic benefits of the climatic impact. In addition, there may be an increase or decrease in employment and economic activity caused by climatic changes which affect timber availability. These are the socio-economic impacts or indirect effects of the climatic change.

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[2] Other examples of economic distortions include pollution, the use of forests for recreational purposes and the use of forests as scenic amenities. The reason the latter two create distortions is that they are not adequately priced in the market, if at all (Brown and Daniel 1986).

The current method for identifying and measuring indirect effects is via input-output (I-O) models (Arthur et al. 1986, 1987; Parry et al. 1987; Williams et al. 1987), but these effects are not to be confused with benefits. In many economic studies, indirect effects obtained from I-O models are often incorrectly included as a part of economic benefits. This is inappropriate as it requires the mixing of two tools which are philosophically and analytically designed to address different issues; these tools are applied welfare analysis - the study of economic efficiency or measurement of benefits and costs - and input-output analysis.

With I-O analysis, indirect effects (or secondary impacts or regional "benefits") are calculated by increasing the appropriate category of final demand in the regional I-O model, with households exogenous. After reconstruction, this gives the increase in value-added occasioned by the type of expenditure in question. Only new processing industries are not treated this way since their development would alter the structure of the economy and, therefore, the I-O models. The value-added is then taken as a net indirect benefit in the B-C analysis. However, value-added is not a measure of benefit; it is merely the upper limit on the opportunity cost of the resources employed in the various activities which generate the value-added. Value-added constitutes only an income transfer or indirect effect, and not an economic benefit (Stabler et al. 1987).

Simulations using the input-output model produce estimates of impacts on the economy in question. The increase in value-added is one component of these impacts. However, impacts cannot be taken as net benefits. Specifically, value-added typically fails to take into account the opportunity cost of the resources used to generate this value-added - the I-O analysis only generates "benefits," but provides no information about costs - and this leads to a substantial overstatement of benefits.

If climate-induced increases in forest output occur, but the economy is at full employment, the increase in employment generated in some sectors of the economy (other than forestry and as determined from the I-O model) constitutes a loss in other sectors. That is, despite an I-O result indicating increased employment, there is no new employment generated, only a transfer from one sector to another. If there is persistent unemployment of resources, particularly labor as may be the case in natural resource dependent regions, then the induced employment (indirect effects) could be included as a socio-economic plus due to the climatic change. However, it needs to be determined if unemployment is indeed persistent and, if it is, whether the cause is structural (e.g. poorly trained labor force) or not. If unemployment is related to structural causes, then an increase in forestry output, for example, may do nothing to alleviate regional unemployment. If the regional labor force is unable to supply the skills required, labor will simply be attracted from other regions (an interregional transfer) or other countries. Indirect effects are obviously pecuniary if this is the case. Even if unemployment is not structural, it is not clear that forestry projects resulting from the increase in timber availability can be used to alleviate unemployment. The time required between authorization of projects to take advantage of the increased timber availability and construction of these projects may simply be too long (Burns and Grebler 1984).

To summarize, input-output models are inappropriate for estimating economic benefits, and this approach is incompatible with applied welfare economics (benefit-cost analysis). The latter is the correct methodology to use in evaluating the net benefits of changes in climate affecting the boreal forest. Even the social accounting model, which is an improvement over the I-O methodology, but is similar to it, "does not capture the behavior of economic agents interacting across markets in response to shifts in price signals... The model is demand driven and completely ignores issues of resource allocation, productivity, and factor utilization" (Adelman and Robinson 1986:1206). Rather, it is necessary to develop computable general equilibrium (CGE) models if one wishes to correctly estimate secondary or indirect effects (Shoven and Whalley 1984). However, such models rely heavily on economic theory, and hence may be outside the purview of many B-C practitioners (e.g. planners, engineers), and they are expensive and difficult to construct. Nonetheless, Kokoski and Smith (1987) employ this procedure in determining the welfare impacts of climatic change.[3]

2.10.2 Methods for Estimating Economic Benefits

A number of methods for measuring the net benefits of climatic change were used in previous studies. We have already considered one of these approaches, namely, I-O analysis; but, as pointed out in that discussion, impacts are often identified rather than benefits. This is the case for some of the approaches discussed below, although it depends upon the particular investigator. In addition, we identify a dynamic optimizing framework for studying the economics of climate change; to our knowledge, this approach has not been used previously in this context. A dynamic optimizing model for the current study is developed in Section 3.5.1. We leave to Section 3.5.2 the issue of what is to be measured. We also do not reconsider the I-O methodology as it has been addressed above.

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[3] This is discussed in more detail in Section 3.5.2.

Econometric Modelling. Econometric modelling employs an a priori specification of economic behaviour and a theoretical relationship among the economic variables. Economic data is then used to estimate numerical values for the coefficients of the variables in the economic relationship. In essence, econometric modelling attempts to empirically describe economic processes.

This conception of econometric modelling clearly indicates that, as the behaviour of economic activity is more aggregated, the linkage between the econometric model and the economic theory becomes more difficult to describe and estimate. It is this aspect of econometric modelling that forces econometricians to resort to models that are more disaggregated. One finds this arising in the econometric models that exist in the forestry industry.

The present study concerns itself with the forest industry as a whole. As indicated in Chapter 1, the economic activities of the forestry industry are numerous, each with its own economic behaviour. As a consequence, models are generally constructed for only one aspect of the industry. An example of this can be found in Singh and Nautiyal

(1984), who consider only the Canadian pulp and paper industry and are primarily interested in price formation, not the type of welfare measurements discussed above.

Adams and Blackwell (1973) and Robinson (1974) also developed econometric models for forest products in the United States. Adams and Blackwell's model considered only lumber, plywood, saw logs and veneer logs and stumpage, excluding the pulp and paper industry. This model was designed to link to a large, econometric, macroeconomic model of the United States. Nevertheless, it only included some of the economic activities of the forestry industry. Robinson's model only considered Douglas fir and Southern pine lumber, and stumpage markets in the United States.

As is pointed out in Lovell and Smith (1985), one of the difficulties in applying econometric models for economic impact analysis is linking the action, in this case climatic change, and its implications for the model. One model, which has this potential, was developed for the Swedish forest sector in Johansson and Lofgren (1985). This model divides the market into two distinct but interrelated markets, the market for sawtimber and the market for pulpwood. Demand and supply curves for each market were estimated. However, the market model is based on price and production costs and not on resource inventory. The effect of climatic change is on inventory and, thus, this variable must play an important role in an analytic model of this kind.

An additional problem with some econometric models is that they are often short-run models. Short-run models are not appropriate for analyzing the implications of a phenomenon such as climatic change whose effects can be long-term. Lonnstedt (1986) constructed a long-term model of a forest sector with an application to the Swedish case. The model was developed as part of a Forest Sector Project at the International Institute for Systems Analysis (IIASA). The model was constructed for a generic forest sector which could be modified to fit the country under investigation. The model includes a forest sector for competing countries and thereby incorporates the forces of international trade. The model covers all activities, ranging from timber growth to the markets of individual forest products. In this respect, Lonnstedt's model is not only a long-term model but is also very aggregated. The demand and supply curves are not estimated directly and adjustment would be required to use this model to measure economic benefits. However, this can be done.

The model is not completely specified in Lonnstedt, but a full-length description is available. Although a detailed examination of the complete model was not carried out, the specification given in Lonnstedt was sufficient to indicate that this model, though theoretically feasible, is not practically feasible. For instance, the model does not consider changes in long-term supply due to environmental considerations, which is precisely what a study on climatic change impacts attempts to accomplish. Hence, that portion of the forest sector model would have to be developed and incorporated into that model. This aspect alone is a project in itself. However, if the resources were available to undertake such a project, this model does include a module which determines inventory of standing volume, increment and total drain. It is within this module that the impacts of climatic change on acreage, mortality (fire, pests and precipitation loss) and changes in silviculture would be incorporated. Lonnstedt also suggests that disaggregation of this module into age classes, qualities and species is possible.

The model as a whole would be extremely large if an attempt were made to accommodate all the aspects required in this study. The entire model would have to be reestimated as well. It would also have to be readjusted for the regional nature of this study. The systems-nature of the model makes it more suitable as a national model. The major drawback to this model, however, is its size and the time required to modify it to meet the objectives of the climatic change study.

There are very few models of the Canadian forest sector that are as encompassing as that of Lonnstedt. Furthermore, as stated in Chapter 1, the geographical area of study to assess the impacts of climatic change is the Prairie Provinces and Northwest Territories. The model used to analyze these impacts should therefore be regional. One such model for Canada is NA-TAMM[4] which is being developed by the Forest Economics and Policy Analysis Project (FEPA), located in Vancouver, British Columbia. NA-TAMM is an expansion of the Canadian block of the U.S. model TAMM.[5] In addition, FEPA is developing a Growth-Drain model which is a forest inventory projection system.[6] The Growth-Drain model will be the source of inventory forecast for NA-TAMM.

NA-TAMM identifies six forest product and timber supply regions.

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[4] North American Timber Assessment Market Model.

[5] Timber Assessment Market Model.

[6] Documentation regarding NA-TAMM and the Growth-Drain Model at FEPA was communicated personally. These reports are only in draft stages and therefore are not referenced nor can they be circulated without the permission of the authors, S.E. Phelps and G. Merkel, respectively.

These include B.C. Coast, B.C. Interior, the Prairie Provinces, Ontario, Quebec, and the Atlantic provinces. NA-TAMM also specifies five demand regions for lumber and plywood, namely, B.C., the Prairie Provinces, Ontario, Quebec, and the Atlantic provinces. Roundwood demand is calculated as a derived demand from lumber and plywood production, pulp products, log exports and imports, and miscellaneous products. The analytic model for the Canadian pulp market to be incorporated into NA-TAMM is still in the developmental stages. Similarly, the Growth-Drain model is a regionally-based model. Should NA-TAMM be used to study climatic change, the Growth-Drain model would have been its most important aspect. Climatic change impacts would appear in nearly all of the factors in the model. Since NA-TAMM is designed to accommodate this particular inventory model, the Growth-Drain model would have to be employed in order to use NA-TAMM to measure economic benefits.

NA-TAMM is a hybrid of an econometric model and a transportation model. The transportation aspect of the solution procedure permits the estimation of a spatial equilibrium. For example, after an exogeneous shock to the forest sector through one of the components of the model, say a fundamental change in forest growth in a particular region, the model can be recalibrated to a new equilibrium. The parameters of demand and supply for various forest products and stumpage are econometrically estimated in each demand and supply region. Stumpage demand and the forest product markets are related through stumpage prices and the sum of roundwood input requirements (log to product recovery factors) for the various products.

A technique called "reactive programing" is used to find a spatial equilibrium for the forest products market. The reactive programing algorithm begins with a trial solution which feeds back to the producing regions. In each producing region it is then determined if any change in production or distribution can yield greater profits. The process is iterated using the new levels of production, and hence new levels of stumpage demand, until no producing region can improve profits. The solution achieved maximizes profit for producing regions and also minimizes transportation costs of product shipment.

The fact that NA-TAMM is still in development, though it has been calibrated, is the major drawback of this model. The Growth-Drain model, which would be so crucial to the climatic change study, is in a very early stage of development. These factors also impinge on the accessibility of the model and knowledge about the ease with which it would be able to be modified to suit the needs of the study.

All of the above models have characteristics which prompted a fundamental criticism by Lucas (1976). Lucas argues that, assuming the structure of the econometric model yields optimum decision rules, any systematic change in the information feeding into the model will alter the structure of the model and, therefore, render the parameters of the model invalid. Parameter estimates based on past data may be no longer valid after the change in environment since the optimal decision rule will change when the structure of the economic process changes. While this may be of only slight significance to short-term projections to a structural change, he argues that in the long-run the consequences may be very significant. As was pointed out earlier, climatic change impact assessment requires a long-term model.

In response to this criticism, econometric models were developed which incorporated the rational expectations hypothesis. The hypothesis was initially suggested by Muth (1961). Since the Lucas (1976) criticism, econometric methodology has been developed to estimate such models (Lucas and Sargent 1981). The basis of the hypothesis is that, at any given time period, economic agents optimize their behaviour using the current information, and the optimum decision at the current time period is the mathematical expectation of some objective function. Ideally, the random component of the model will have zero expectation since all systematic information will be contained in the structure of the model and only unanticipated changes will arise.

Epple (1985) provides an excellent example of such a model. The model yields an optimum plan for the extraction of an exhaustible resource. It is applied to the case of petroleum. The solution maximizes the objective function of the resource extractor; the objective function to be maximized is the sum of expected present value of net revenues over the lifetime of the resource base. Producer's expectations regarding prices and costs are treated explicitly, as are the characterizations of the optimal extraction paths.

Such a model could be adapted to a renewable resource such as the forest sector. In the case of climatic change, the objective function would be the sum of discounted expected economic benefits from the present to infinity.[7] An important aspect of Epple's model is the characterization of the producer's expectations, that is, the information set upon which the producer bases his decision. The parameters of the optimal decision rules are dependent on the parameters of the price and cost equations in that information set. Hence, as the information set changes, so does the structure of the economic process and the optimum decision path. This characteristic makes such a model dynamic in the sense that the parameters of the decision rules are updated each time period, based on current and past information.

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[7] The objective function is discussed in greater detail below.

There are several ways in which an estimated econometric model can be used to measure economic benefits. Some econometric models directly estimate supply and demand. New values of exogeneous variables, say climate, will yield a new supply curve and one can then calculate the change in economic surplus. One could also calculate an impact multiplier, then change the value of an exogeneous variable and find a new equilibrium solution. This would yield new values for the endogeneous variables, such as output, price and revenues. These are comparative static techniques and would not capture the dynamic process the economy undergoes to achieve the new equilibrium. They also assume no structural change in the economy as a result of climatic change. (This is also a problem in I-O analysis.) As stated earlier, the measurement of economic benefits usually requires a general equilbrium model. The above models are all partial equilibrium models, though that of Adams and Blackwell (1973) was designed to link to a macroeconomic model.

Still other econometric models such as that of Epple (1985) can directly compute economic benefits as the solution to a maximization problem. The rational expectations approach to econometric modelling is the most theoretically sound for application to long-term, structural, renewable resource modelling. The similarity of the rational expectations approach and that of dynamic optimization models is evident in the following sections.

It should be noted that econometric models tend to be very specific in nature and are designed to address very specific questions. As a result, they tend to be difficult to modify and, often, it is expedient to construct an econometric model that is particular to the study in question.

Linear Programing (LP). In assessing the impact of climatic change on agriculture in the Canadian prairies, Arthur et al. (1986, 1987) employ the Versatile Soil Moisture Budgets of Agriculture Canada to determine changes in available soil moisture caused by climatic change. Yield for major prairie crops is then regressed on various climatic, physical and technological variables, with the results used in an on-farm LP model to determine changes in optimal cropping patterns. The net economic benefits are found by determining the difference in net farm incomes under the various climatic scenarios.

The major problem with this approach is that it is static, and may be unable to handle weather phenomenon as these are dynamic. However, this tool is a popular one and is understood by many foresters; it has been used in many studies to solve forest management problems. However, LP has several limitations (Buongiorno and Gilless 1987:169). First, LP is a static optimizing technique and is not really appropriate for analyzing dynamic problems such as those encountered in forestry.[8] Second, it applies only to variables that are continuous. If discrete variables are present, which is inevitable in forest management, linear programing cannot be employed, although it is possible to use integer programing in this case. Finally, LP can only use linear relationships, and these have been shown unrealistic in the case of growth of a natural resource system (Walters 1986). The major advantage of LP is that there are readily available, off-the-shelf computer programs for solving LP problems.

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[8] It should be noted that dynamic problems can, in some cases, be solved using LP. However, the major technique in these cases is still a dynamic one, not a static one such as LP.

Dynamic Optimizing Models. Dynamic programing is an approach to optimization that can handle nonlinear relationships and discrete variables (Buongiorno and Gilless 1987:169). The disadvantage is that, unlike LP, there is no standard form and, therefore, there are no computer subroutines that can be taken from the shelf and used in problem solving. Despite this, dynamic programing, for example, has become a popular tool for forest management.

The correct method for measuring the benefits of climatic change is to compare the present value of economic surpluses under different, and perhaps changing, climatic conditions. This requires that a dynamic optimizing model be employed. Bowes and Krutilla (1985), and Reed (1986), review methods for determining optimal harvests and timber management solutions. These methods are dynamic and generally employ optimal control theory. For example, Lyon and Sedjo (1983) employ the concept of economic surplus - the sum of the welfares of consumers and producers - to determine an optimal forest rotation.

Various techniques for solving the optimal control problem have been suggested depending upon the purpose of the research. In many cases, researchers have been concerned primarily with optimal trajectories for harvest over time and under alternative scenarios regarding the size of the stand, presence of multiple species, the functional form of the growth curve, etc. However, few studies that we are currently aware of attempt to provide actual numbers to the dynamic models.[9] Dynamic programing (DP) seems to hold the most promise for the current analysis. Riiters et al. (1982) employ this method in analyzing forest management strategies. We believe that it is necessary to develop a dynamic model, perhaps a DP model, if one is to assess the impacts of climatic change on forestry. We do this in the next chapter.

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[9] An exception appears to be Riiters et al. (1982).

3 DATA AND METHODOLOGY- THE USE OF CLIMATIC CHANGE MODELS, IMPACT AND ECONOMIC MODELS

3.1 Climatic Change Scenarios

3.1.1 Selecting and Designing Climatic Change/Variability Scenarios

Various types of climatic scenarios can be used to depict a warmer climate as may be expected with a doubling of atmospheric CO_2. A climatic change scenario has been defined as a description of the spatial patterns and seasonal behaviour of temperature, precipitation and other important meteorological variables in an altered climatic state (Santer 1985). Climatic change scenarios of various types have been used. These can be classified as follows: 1) historical analogues, 2) synthetic, 3) GCM-derived and 4) hybrid climatic change scenarios.

Historical analogues are especially useful if there is a sufficient length of record for the selection of extremely anomalous periods. They may also be constructed from paleoclimatic data based on proxy information such as that from tree rings and ice cores. A set of these scenarios can be quite flexible, as they may use single anomalous years, an extreme decade or an extreme period of years. They also have the advantage of representing conditions that actually occurred in the past. The past has often been viewed as the key to the present and the future. Furthermore, because they can occur in the next season or year, these scenarios have greater implications for the near future than do the GCM scenarios of enhanced CO_2, for example.

However, scenarios based on past records of climate are not very suitable in the context of changes in atmospheric chemistry. Because such elevated levels of CO_2 as double the pre-industrial amount have not occurred in the historical past, the warmer historical periods must have been caused by other mechanisms. Therefore, they may not even come close to duplicating the characteristics of a warmer climate caused by the "greenhouse-effect" gases. In addition, the projected warming is greater and more uniform globally than any period in the historical record.

Synthetic climatic change scenarios can be created by combining and/or adjusting historical data. A synthetic series can be created by selecting single anomalous years, seasons, etc. and placing them consecutively in a sequence. This type of scenario can also be constructed by adjusting historical data by increasing temperature arbitrarily by a certain range of degrees and increasing rainfall by certain percentages, for example. This may be one way of forcing the historical data to conform to what may be an enhanced CO_2 level; but it may result in the analysis of an excessive number of combinations of temperature and precipitation, some of which may have a low probability of joint occurrence and may not have CO_2 as the driving mechanism for the change.

Thus some impact modellers have turned to the GCM simulations to provide sets of perturbed climatic data as inputs to impact models. The GCM results provide a powerful technique to explore the nature of climate in a warmer world because they overcome many of the problems inherent in the use of the previously mentioned types. Their usage also entails the following advantages that are not mentioned above: 1) data are provided on a uniform grid point basis so the network uniformity is optimum, and 2) data are simulated which may not exist at some stations (e.g. some stations do not have precipitation records).

There are, however, several problems in using GCM results in estimating climatic impacts. One of these is that the 1 x CO_2 results often do not conform well to the observed climate (Williams et al. 1987; Wilson and Mitchell 1987). It is usually inappropriate to use GCM results for 1 x CO_2 and 2 x CO_2 **directly** as inputs to impact models. This problem may be overcome by using the difference between (for temperature) and ratio of (for precipitation) the 2 x CO_2 and the 1 x CO_2 GCM results as adjustments to historical data. The historical data and the adjusted data are then used to simulate the 1 x CO_2 and the 2 x CO_2 climates, respectively. Hopefully, the comparison between the two simulations better indicates what the perturbed climate may be like. GCM modellers are also striving to improve their ability to simulate climatic reality given the complexity of the atmospheric-oceanic-geographic (e.g. vegetation, land form, hydrology) system to be modelled and of the computer requirements for such work.

Another problem with using GCM results is that data that have been calculated for climatic parameters, such as wind, atmospheric circulation and evaporation, may not be available to those doing the impact studies. As communication between the GCM and impact modellers is improving, this problem is diminishing.

Inadequate spatial resolution is also a limitation of GCM results. Data are not available for the smaller regional areas but only for widely spaced gridpoints. Spatial interpolation can be used in calculating the differences and/or ratios for applying the historical data for small areas (Williams et al. 1987), but this does not overcome the basic problem of lack of sufficient spatial resolution of GCM results.

Inadequate temporal resolution is another shortcoming of GCM results. Data are available only as monthly or seasonal means. A knowledge of extreme events and their frequencies, rather than just means, is also useful to impact modellers and is economically significant; examples are frost and strong winds (Wilson and Mitchell 1987).

Little or no information exists regarding the statistical distribution of the parameters (distribution type, variation, etc.). Usage of the GCM results, in absence of this information, also entails invoking several assumptions, for example, that the changed climate will have the same variability as the past climate.

More information is needed about the climatic response to an increase in CO_2 over time (Santer 1985). This would provide more than just a snapshot in time at the 2 x CO_2 level.

These are just some of the problems that are especially important in impact studies. Many of them can be overcome, however, by using hybrid climatic change scenarios as described below (Maybank et al. 1987). So there is certainly a great deal of impact assessment that can be done in the meantime. In many cases, the impact models are at as early a developmental stage as the GCMs, or they do not even exist in many instances.

The use of hybrid climatic change scenarios may sometimes be more realistic than employing those based on the GCM results alone. Williams et al. (1987) have used this type in agricultural impact assessment. These hybrid scenarios are an effective combination of two or more types, such as the GCM derived scenarios for some parameters and historical and or synthetic data for others.

Hybrid climatic change scenarios are especially useful when some necessary parameters for an impact model are not available from the GCM results or when a parameter has been modelled with somewhat less confidence than desired. For example, Williams et al. (1987) used a combination of temperature adjustments based on the Goddard Institute for Space Studies GCM experiments (Hansen et al. 1984) and historical precipitation data. Hybrid scenarios can help overcome the spatial, temporal, geographic and snapshot problems encountered when using the GCM results only. So while the climatic modellers proceed to improve the GCMs, the impact modellers also have a wide variety of techniques to use in making the much needed improvements in their own modelling.

3.1.2 Climatic Change Scenarios Chosen to Simulate Climate for 2 x CO_2

The climatic change scenarios used in this study are the GCM-derived type that utilize both the normal and GCM climatic data - the hybrid type, as discussed previously. The 1 x CO_2 and 2 x CO_2 GCM equilibrium climate adjustments (differences for temperature and ratios for precipitation) and the normal climatic data for gridpoints, including the study area, were provided by the Canadian Climate Centre (Street, pers. comm.). The reasoning behind using these adjustments rather than the GCM data directly is presented in Williams et al. (1987, sec. 1.5.2). The GCM results are from experiments undertaken by the Goddard Institute of Space Studies (GISS) and the Geophysical Dynamics Laboratory (GFDL). Therefore, the climatic change scenarios based on these models are termed GISS1 and GFDL1 for ease of discussion and presentation.

The other climatic data required for the impact models were not available from the GCM results. Thus, the most recent climatic normals and standard deviations from Environment Canada (1982, 1987) publications were used.

The GCM results were also used to create hybrid climatic change scenarios. Temperatures were increased as for the GISS1 and GFDL1 scenarios, but the normal precipitation values were used. These scenarios are labelled GISS2 and GFDL2. They were selected because the projections of precipitation amounts from GCMs are less certain than temperature projections and that the precipitation projections may be high as compared to historical data. Historically, high temperatures have been found to be associated with low precipitation amounts (Villmow 1956; Robertson 1974). These studies are only applicable to the southern part of the study area and the relationship between temperature and precipitation for the study area should be determined. In the interim, however, the use of such additional scenarios is a means of expanding the sensitivity analysis as well as to emphasize the uncertainty of the scenarios.

A reference is needed against which results of analysis involving these scenarios can be compared. The reference used is the standard climatic scenario based on the most recent normal period, 1951-1980. This reference is referred to as HIST.

3.2 Productivity Data for Impact Models

Forest productivity data for the study area are limited in availability. The only data available for the whole area were compiled by Bickerstaff et al. (1981), and consist of estimates of mean annual increment (average for productive forest land) for each of Rowe's (1972) forest sections. According to personnel of the FORSTATS program at Petawawa National Forestry Institute, updated versions of these figures will be available in early- to mid-1988. A set of similar figures, broken down by forest cover type and survey area in Saskatchewan, have been made available by the Saskatchewan Forestry Branch.

The Canada Land Inventory (CLI) mapped land capability for forestry in much greater detail than the above data for the more accessible parts of the forest land in the Prairie Provinces (Kabzems et al. 1972). The CLI ratings were ostensibly based on mean annual increment classes, but much of the mapping was based on interpretation, so may not be usable.

Yield tables and site index curves are available for forest cover types in Alberta (Alberta Forest Service 1985) and Saskatchewan (Kabzems and Kirby 1956; Kirby et al. 1957; Kabzems 1971; Benson 1973). Unfortunately, these are standard yield tables for the respective provinces, so carry little information on geographic variation. Equations for predicting biomass and its components from diameter and height for the boreal species have been prepared by Singh (1982).

Under the International Biological Programme, complete ecosystem measurements, such as net primary productivity, were made for sites around the world. But few of these were in the boreal zone and none in the study area.

Physiological information on the boreal species is limited. Response curves for photosynthesis and respiration to light and temperature are available for black spruce (van Zinderen Bakker 1974; Vowinckel et al. 1975; Black and Bliss 1980), white spruce (Clark 1961), and balsam fir (Clark 1961; Fryer and Ledig 1972).

3.3 Selection of Impact Models

It is advisable to have a set of selection criteria in situations where one is fortunate enough to have existing impact models. These can also be used in developing models.

A useful discussion of the selection of impact models appears in Williams et al. (1987). The selection criteria they used includes relevance to the study area, flexibility, applicability to macroscale analysis, sensitivity to changes in the variables analyzed, existence in a practical, operational form, and efficiency and economy of use.

These criteria, along with several others, may be put in matrix form against the names of the models and used to aid in comparison of the models. The other criteria deemed suitable include whether the data requirements are realistic, whether they are physical or empirical, their degree of flexibility and documentation, and whether or not they use climatic and climatic change data. Appendix B provides more detailed notes on evaluating the usefulness of various models for the purposes of this study. The most promising models can be selected for impact assessment using this assessment methodology. Also much information about the models can be effectively conveyed to the reader/user if such a matrix is provided.

3.4 Climatic, Productivity and Zonation Impact Models

Several climatic impact models were used for the climatic change impact assessment. The modelled results include growing degree-days (5°C threshold), precipitation effectiveness, and the climatic index of agricultural production (CA), along with the numerous factors used to calculate CA such as the soil moisture deficit, evapotranspiration, and the dryness, solar, thermal and heliothermic factors.

Only the growing degree-days were calculated for all of the gridpoints within and surrounding the study area because of time limitations. Therefore, at least one representative point was chosen to provide data for each forest zone for each of the scenarios. All of the appropriate gridpoints should be used in future analysis, if possible, in order to better assess spatial patterns.

Growing degree-days (GDD) are selected because of their long history of characterizing the thermal climate for vegetation, both in Canada and internationally. Growing degree-days are indicative of both growing season length and temperature. They have been used in another climatic change impact on forestry study (Kauppi and Posch 1985) for similar reasons. The calculation of GDD in this context of climatic change is explained in Williams et al. (1987).

The precipitation effectiveness index of Thornthwaite (1931) is also relatively simple to calculate, uses available data and is suitable for displaying spatial patterns. It is a function of both temperature and precipitation, in which evaporation is expressed in terms of temperature and was derived from empirical data. An advantage of this index, for our purposes, is that it was designed for a climatic classification in relation to vegetation and soil classifications, and is useful for characterizing spatial patterns of large areas. Newer versions of this model, such as the one used by Environment Canada (Mapanao and Louie 1986) with modifications to improve relevance to the study area, should also be examined.

The climatic index of agricultural potential (Turc and Lecerf 1972), CA, reflects both thermal and moisture resources and is computed by summing the 12 monthly products of heliothermic and moisture factors as follows:

$$CA = \sum_{i=1}^{12} T_i * Fs_i$$

HT is a heliothermic factor including both temperature and solar parameters, Fs is a soil moisture factor computed using precipitation, and temperature in a climatic soil moisture budgeting procedure and i indicates months.

Fs is 0 for very dry conditions and increases to 1.0 for plentiful moisture; excesses of moisture are ignored. HT has only a lower limit; it is 0 where the mean daily minimum temperature for the month is 0°C or lower, and above this value, it increases with increasing temperatures. Thus, CA reflects the length of the growing season and the amount of heat and moisture available to plants during the season. It is indicative not only of the agricultural potential of the climate, but also of the potential for biomass productivity in general, including forest productivity (Turc and Lecerf 1972).

Another advantage of this model is that it can be used to explore changes in biomass in general and is not limited to one vegetation type. Considering that climatic change may be accompanied by a shift in vegetation zones, this capability is very appropriate.

The term biomass productivity is used here as equivalent to total harvestable dry matter, which would include the weight, after drying, of all plant material. Turc and Lecerf (1972) suggest that each unit of CA is equivalent to dry matter production of about 0.6 tonnes per hectare. This value can then be adjusted by a harvest index in order to indicate the harvestable timber.

Monthly and annual values of CA, Fs and HT were computed for gridpoints in the study area for several climatic change scenarios and for the normal climatic data. The required data include monthly averages of daily mean temperature, daily minimum temperature, monthly total precipitation, average monthly global solar radiation, and median monthly daylength. The solar radiation data were not adjusted, so it is assumed that the solar radiation remains the same. The mathematical basis of CA is explained in detail in Williams (1985) and Williams et al. (1987).

Two other modelling exercises using partial data were carried out to demonstrate approaches that can be carried further in future work. The first model is a simple regression of forest productivity on climatic data in the study area. The productivity data are from Bickerstaff et al. (1981) and consist of estimates of the mean annual increment (MAI) for productive forest land in each of Rowe's (1972) forest sections. The climatic data are given by Rowe for sample stations in the forest sections, and consist of annual precipitation (PPT) and Thornthwaite's potential evapotranspiration (PE). The latter is an estimate of the evapotranspiration that would occur if soil moisture was not limiting, and mainly reflects growing season temperatures. The climatic data were used to construct a simple index of moisture, (IM): (PPT/PE)*100.

Twenty-one values of MAI could be matched with climatic data given by Rowe for stations in the Prairie Provinces or Northwest Territories. These ranged from grassland and aspen parkland in the south to subarctic woodland and forest-tundra in the north. Multiple linear regression analysis was used to relate MAI to PE and IM as follows:

$$\ln(MAI) = -27.5 + 3.43*\ln(PE) + 1.41*\ln(IM)$$

$$R^2 = 0.75$$

The productivity of some sections is undoubtedly affected by geological conditions controlling the distribution of sites. In an attempt to account for this effect, a binary variable was created, with values of zero for the forest sections with large proportions of peatland (B.14, B.15, B.21) or exposed bedrock (B.22a, B.27, B.32), and one for other sections. This variable was also tested as an independent variable in the multiple regression. However, inclusion of this variable in the regression only increased the R^2 to 0.78.

The second model dealt with climatic determination of the zonation of the boreal forest. The zones used were the broad ones indicated by Rowe (1972): tundra, forest and barren (i.e. subarctic woodland and forest-tundra), boreal forest, Great Lakes-St. Lawrence forest (i.e. boreal-temperate forest), forest and grassland (i.e. aspen and aspen-oak parkland) and grassland (Figure 1.1). The distribution of these zones was compared to isolines of growing degree-days above 5°C (Figure 4.3). The northern boundaries clearly parallel these isolines, and could be approximated by 600 growing degree-days for the border between tundra and subarctic, and 1000 growing degree-days for the border between subarctic and boreal forest. The southern boundary of boreal forest with boreal-temperate forest in eastern Canada can also be approximated by the 1400 degree-day isoline. However, the southern boundary with grassland in western Canada does not match the isolines; rather the transition to grassland occurs at higher temperature-sums in more humid Manitoba and lower temperature-sums in drier Alberta, suggesting that moisture availability is the critical factor.

To quantify this pattern, 22 stations were located along the grassland/parkland boundary, and 19 stations along the parkland/boreal boundary, distributed across the three provinces. Data for annual precipitation and growing degree-days above 5°C were obtained for each station from Environment Canada (1982). For each set of data a simple linear regression of growing degree-days on precipitation was calculated. This regression expresses the increasing temperature-sum required to produce the boundary as precipitation increases. The regression for the grassland/parkland boundary has an R^2 of 0.57, while that for the parkland/boreal boundary (which is less clearly defined) has R^2 of only 0.18.

The use of these relationships to define vegetation zones is shown in Figure 4.4. Results of the application of these models are provided in Chapter 4.

3.5 Economic Research Component

In Section 2.10 a general discussion of the appropriate methodology to employ in an investigation of the economic impacts of climatic change is provided. Previous studies which have examined the economics of climate are considered, as are studies that employ methodologies which might prove useful in an investigation of the economics of climatic change. Although some studies are discussed in detail, the focus is on their usefulness in the current context. Many studies of climatic change focus on agriculture, but there is some similarity between the problems addressed there and those addressed in this study. However, the methodologies employed in the previous studies are inadequate and sometimes incorrectly motivated; arguments as to why this is the case are provided. In particular, it is felt that a dynamic model is required to address economic issues associated with climatic change.

Therefore, a dynamic model for measuring the potential benefits of climatic change is presented in Section 3.5.1. This is because the proper measure of the benefits of climatic change is obtained by comparing the benefits of forest production along one optimal path with those along another, where the two paths represent current and alternative climatic scenarios. The model is a discrete time optimal control (DTOC) model. Solution methods are also discussed in Section 3.5.1.

In Section 3.5.1, a general benefit function is assumed. However, it is necessary to determine what economic benefits and costs are to be measured. This is the subject of Section 3.5.2. In particular, benefits and costs are compared under closed and open economy models, with a trade distortion also considered in the latter case. The analysis in this section also provides an indication of the problem with the previous methods of analysis. Finally, the nonmarket functions of the boreal forest are examined in Section 3.5.3. The forest provides services, such as wildlife habitat, water storage, weather regulation,pollution abatement, etc., which may be more valuable than the commercial timber values which are the focus of the earlier sections. It is likely that changes in the values of the nonmarket functions of the forest, changes brought about by climatic changes, may be larger than any changes in commercial timber value resulting from the climatic change. However, the main problem is that these services or amenities are not priced in the market. Therefore, methods for determining these nonmarket values are examined.

3.5.1 Dynamic Forest Models for Analyzing Climatic Change Impacts

In this section, we develop a management model for the boreal forest which can be used to investigate the economic benefits of climatic change impacts on the boreal forest. The model can also be adapted to take into account insect pests and forest fires. However, doing so will require a concerted research effort on the part of scientists. The model is an extension of one developed by Lyon and Sedjo (1983), but we extend the model by introducing the concept of a Leslie equation (Leslie 1945, 1948), which can be considered the dynamic constraint. The Leslie equation may prove useful for solving the multiple species, probabilistic model which will be required in later phases of the research. The objective function, or the economic criterion used in the model, is discussed in greater detail in Section 3.5.2. A discussion of other dynamic models employed in forest management can be found in Bowes and Krutilla (1985) and Reed (1986).

We begin by considering the model of Lyon and Sedjo (1983), and extend it to include climatic factors. The model is solved analytically to illustrate some important economic and physical requirements for an optimum, and to provide a basis for solution algorithms, which is the topic of the latter part of this section. We also illustrate how the constraint in the model can be formulated for practical application as a Leslie equation. The Leslie equation allows for consideration of stochastic events (e.g. stochastic price, yield), nonlinearities and so on (Pielou 1977; Pollard 1966; Usher 1966, 1969, 1972).

3.5.1.1 The Lyon-Sedjo Model: An Extension

The objective of social decision makers is to maximize some benefit function related to the forest resource. This benefit function can be written as follows:

(1) $B_t(v_{jt}, x_{jt}, u_{jt}, m_{jt}, c_{jt})$,

where v_{jt} is the volume of commercial timber available from trees t years after regeneration (i.e. after previous harvest); x_{jt} is the number of acres of timber of "age" j available at time t;[1] u_{jt} is the proportion of acres of age j years since regeneration to be harvested at time t; m_{jt} is the management decision regarding regeneration at the time timber, now j years from regeneration, was being regenerated;[2] and c_{jt} is the climate experienced by trees of age j years since regeneration at time t. The benefit function can be defined in a variety of different ways. For example, Lyon and Sedjo define the benefit function to be the sum of consumer and producer surpluses. The actual form of the benefit function is considered in a later section.

The number of acres of timber of age j+1 at time t+1 will depend upon the number of years since regeneration (since last harvest), the number of acres of timber of age j in the previous year, and the number of acres of timber of age j harvested.

(2) $x_{j+1,t+1} = x_{jt} - u_{jt}\, x_{jt} = (1 - u_{jt})\, x_{jt}, (j=1,..,A-1;\ t=0,..,T-1)$

where u_{jt} is the proportion of acres of age j harvested in year t. If

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[1] It is possible that j years after regeneration trees may be older or younger than j. If the management decision for recently harvested trees is to reforest with 2-year old trees, then the trees will be older than j years; if the decision is to allow nature to reforest the region, then trees may be less than j years of age.

[2] Lyon and Sedjo suggest that there are three management decisions to be made after harvesting. The decision maker can (i) leave the harvested acres to regenerate naturally, (ii) seed the harvested acres, or (iii) plant 2-year old trees. In addition, there are management decisions to be made at each period in time. These include decisions regarding thinning, fire control and so on.

p_{jt} is defined as the proportion of acres of timber of age j left standing at time t, then it is possible to rewrite Equation (2) as:

(2′) $$x_{j+1,t+1} = p_{jt}\, x_{jt}.$$

However, the number of acres of timber of age 1 year is equal to the number of acres harvested in the previous year; that is,

(3) $$x_{1,t+1} = \sum_{j=1}^{A} u_{jt}\, x_{jt}, \quad t = 0, \ldots, T-1.$$

Further, the number of acres of trees of age A (the maximum age trees are assumed to attain) at time t+1 is equal to the number of acres of trees of age A at time t plus the number of acres of age A-1 at time t, minus the number of acres of ages A and A-1 harvested at time t.[3] Thus, it is simply assumed that trees of age A which are left standing remain at age A. However, it is further assumed that these trees take on the characteristics of trees regenerated in the previous period - that is, for trees of age A at time t, m_{At} describes their management characteristics.

At time t, a management decision is made regarding the trees harvested in that period. This decision may be to plant 2-year old seedlings, seed the area or do nothing. This decision is denoted by w_t and is represented by the following equation:

(4) $$m_{1,t+1} = w_t.$$

This management decision has an effect on the size of trees beyond the first year after regeneration. That is, the management decision made about trees at regeneration time impacts on the trees as they grow from the time of regeneration. This is represented by the following:[4]

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[3] It is assumed that trees cannot be older than A years of age. While this is obviously not true, it is likely that trees beyond a certain age simply do not grow bigger.

(5) $$m_{j+1,t+1} = m_{jt}.$$

The volume of commercial timber of "age" j available at time t measured on a per unit area basis (i.e. per acre) is a function of the number of years the trees have been growing (j), the management characteristics of the trees growing at time t (m_{jt}), and the climate already experienced by trees of "age" j at time t (c_{jt}); that is,

(6) $$v_{jt} = f(j, m_{jt}, c_{jt}),$$

where f( ) can be considered a production function for timber. It is likely that f( ) increases at an increasing rate over some range of ages, and then increases at a decreasing rate. Thus, the following will likely hold over the range of ages of concern to the decision maker: $\delta f/\delta j>0$, $\delta^2 f/\delta j^2<0$ and $\delta f/\delta A = 0$. In addition, production is a function of climatic conditions and management. It is assumed that growth increases with management, but at a decreasing rate: $\delta f/\delta m_{jt}>0$ and $\delta^2 f/\delta m_{jt}^2<0$.

To find the volume of timber from a particular age category, it is necessary to multiply the production function by the number of acres of trees of this age. Then total volume is obtained by summing over all age categories. The total volume of commercial timber that is harvested in a given year is denoted by V_t and is equal to the number of acres of each "age" category harvested multiplied by the corresponding production function; that is,

(7) $$V_t = \sum_{j=1}^{A} u_{jt}\, x_{jt}\, f(j, m_{jt}, c_{jt}), \quad t = 0, \ldots, T-1.$$

---

[4] It may be that management decisions can be made for every age of tree (e.g. spraying for pests). This can be incorporated into the analysis quite easily, but is not done at this stage.

The objective function is to be maximized over all periods of the planning horizon (t = 0, ..., T):

$$(8)\quad \underset{u_{jt}, w_t}{\text{Max}} \sum_{t=1}^{T-1} [B_t(v_{jt}, x_{jt}, u_{jt}, m_{jt}, w_t, c_{jt})]\beta^t + \Omega\,(x_{jT}, v_{jT})\,\beta^T,$$

where $\Omega(\ )$ is the (salvage) value of the forest at the end of the planning horizon and β is the discount rate. Problem (8) is maximized subject to Equations (2), (3), (4), (5) and (6). In addition, there is a set of initial conditions for the number of acres in each "age" group and the management characteristics for each "age" group, and there are constraints on the values which the variables can take. These constraints are written, respectively, as:

(9) $x_{j0} = a_{j0}$ and $m_{j0} = b_{j0}$ for all $j = 1, \ldots, A$; and

(10) $0 \leq u_{jt} \leq 1$, $x_{jt} \geq 0$, $u_{1t}=0$ and $w_t \geq 0$.

It is assumed that no timber of age 1 period beyond regeneration is harvested.

The Lagrangian for the constrained maximization problem is:

$$
\begin{aligned}
(11)\qquad L = {} & \sum_{t=0}^{T-1} [B_t(v_{jt}, x_{jt}, u_{jt}, m_{jt}, w_t, c_{jt})]\beta^t + \Omega\,(x_{jT}, v_{jT})\,\beta^T \\
& - \lambda_{1,t+1}\,\beta^{t+1}\,[x_{1,t+1} - \sum_{j=1}^{A} u_{jt}\,x_{jt}] \\
& - \lambda_{j+1,t+1}\,\beta^{t+1}\,[x_{j+1,t+1} - (1 - u_{jt})\,x_{jt}] \\
& - \theta_{1,t+1}\,\beta^{t+1}\,(m_{1,t+1} - w_t) - \theta_{j+1,t+1}\,\beta^{t+1}\,(m_{j+1,t+1} - m_{jt}) \\
& - \gamma_t\,\beta^t\,[v_{jt} - f(j, m_{jt}, c_{jt})] \\
& - \phi_{j0}\,(x_{j0} - a_{j0}) - \epsilon_t\,\beta^t\,(u_{1t} - 0) - \Gamma_j\,(m_{j0} - b_{j0}).
\end{aligned}
$$

The Lagrange multipliers are λ_{rs}, θ_{rs}, γ_{rs}, ϕ_{rs}, ϵ_s and Γ_r, where $1 \leq r \leq A$ and $0 \leq s \leq T$. Values of the Lagrangian multipliers outside this range are zero.

The first-order conditions for a maximum of the Lagrangian are as follows:

$$(12)\quad \delta L/\delta v_{jt} = \delta B_t/\delta v_{jt}\ \beta^t - \gamma_t\ \beta^t = 0, \quad t = 0, \ldots, T\text{-}1;$$

$$\delta L/\delta v_{jT} = (\delta\Omega/\delta v_{jT})\ \beta^T - \gamma_T\ \beta^T = 0\ ;$$

$$(13)\quad \delta L/\delta x_{j0} = \delta B_0/\delta x_{j0} - \lambda_{j0} + \lambda_{11}\ \beta\ u_{j0} + \lambda_{j+1,1}\ \beta\ (1 - u_{j0}) - \phi_{j0}=0;$$

$$\delta L/\delta x_{jt} = (\delta B_t/\delta x_{jt})\ \beta^t - \lambda_{jt}\ \beta^t + \lambda_{1,t+1}\ \beta^{t+1}\ u_{jt}$$

$$+ \lambda_{j+1,t+1}\ \beta^{t+1}\ (1 - u_{jt}) = 0, \ t=1, \ldots, T\text{-}1;$$

$$\delta L/\delta x_{jT} = (\delta\Omega_T/\delta x_{jT})\ \beta^T - \lambda_{jT}\ \beta^T = 0;$$

$$(14)\quad \delta L/\delta m_{j0} = \delta B_t/\delta m_{j0} - \theta_{j0} + \theta_{j+1,1}\ \beta + \gamma_0\ [\delta f(\ )/\delta m_{j0}] - \Gamma_0 = 0\ ;$$

$$\delta L/\delta m_{jt} = (\delta B_t/\delta m_{jt})\ \beta^t - \theta_{jt}\ \beta^t + \theta_{j+1,t+1}\ \beta^{t+1}$$

$$+ \gamma_t\ \beta^t\ [\delta f(\ )/\delta m_{jt}] = 0, \ t = 0, \ldots, T\text{-}1;$$

$$(15)\quad \delta L/\delta u_{1t} = (\delta B_t/\delta u_{1t})\ \beta^t + \lambda_{1,t+1}\ \beta^{t+1}\ x_{1t} - \lambda_{2,t+1}\ \beta^{t+1}\ x_{1t}$$

$$- \epsilon_t\ \beta^t = 0, \ t = 0, \ldots, T\text{-}1;$$

$$\delta L/\delta u_{jt} = (\delta B_t/\delta u_{jt})\ \beta^t + \lambda_{1,t+1}\ \beta^{t+1}\ x_{jt} - \lambda_{j+1,t+1}\ \beta^{t+1}\ x_{jt} = 0,$$

$$t=0, \ldots, T\text{-}1;$$

$$(16)\quad \delta L/\delta w_t = \delta B_t/\delta w_t\ \beta^t - \theta_{1,t+1}\ \beta^{t+1} = 0, \quad t = 0, \ldots, T\text{-}1;$$

$$(17)\quad \delta L/\delta c_{jt} = (\delta B_t/\delta c_{jt})\ \beta^t + \gamma_t\ \beta^t\ [\delta f(\ )/\delta c_{jt}] = 0.$$

Notice that, in the foregoing optimization problem, there are two counters - one for time and another for "age" of trees. The problem can, however, be reduced to a single counter by using matrices. Define the following vectors and matrices:

$$X_t = \begin{bmatrix} x_{1t} \\ \cdot \\ \cdot \\ \cdot \\ x_{At} \end{bmatrix}_{A \times 1} \qquad U_t = \begin{bmatrix} u_{1t} & \ldots & 0 \\ \cdot & & \cdot \\ \ldots & & \ldots \\ \cdot & & \cdot \\ 0 & \ldots & u_{At} \end{bmatrix}_{A \times A}$$

$$K = \begin{bmatrix} 0 & 0 & \dots & & & 0 \\ 1 & 0 & \dots & & & 0 \\ 0 & 1 & \dots & & & 0 \\ \cdot & \cdot & & & & \cdot \\ \cdot & \cdot & & & & \cdot \\ 0 & 0 & \dots & 1 & 0 & 0 \\ 0 & 0 & \dots & 0 & 1 & 1 \end{bmatrix}_{A \times A} \qquad B = \begin{bmatrix} 0 & -1 & -1 & \dots & -1 \\ 0 & 1 & 0 & \dots & 0 \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ 0 & 0 & 0 & \dots & 1 \end{bmatrix}_{A \times A}$$

$$F_t = \begin{bmatrix} f_{11}{}^t & \dots & f_{1A}{}^t \\ \vdots & & \vdots \\ f_{A1}{}^t & \dots & f_{AA}{}^t \end{bmatrix}_{A \times A} \qquad V_t = \begin{bmatrix} v_{1t} \\ \vdots \\ v_{At} \end{bmatrix}_{A \times 1} \qquad X_0 = \begin{bmatrix} a_{10} \\ \vdots \\ a_{A0} \end{bmatrix}_{A \times 1}$$

$$J = \begin{bmatrix} 0 & 0 & \dots & & & 0 \\ 1 & 0 & \dots & & & 0 \\ 0 & 1 & \dots & & & 0 \\ \cdot & \cdot & & & & \cdot \\ \cdot & \cdot & & & & \cdot \\ 0 & 0 & \dots & 1 & 0 & 0 \\ 0 & 0 & \dots & 0 & 1 & 0 \end{bmatrix}_{A \times A} \qquad W_t = \begin{bmatrix} w_t \\ 0 \\ \vdots \\ 0 \end{bmatrix}_{A \times 1} \qquad M_t = \begin{bmatrix} m_{1t} \\ m_{2t} \\ \vdots \\ m_{At} \end{bmatrix}_{A \times 1} \qquad M_0 = \begin{bmatrix} b_{10} \\ b_{20} \\ \vdots \\ b_{A0} \end{bmatrix}_{A \times 1}$$

$$e = [1 \ 0 \ \dots \ 0]_{1XA}$$

where F_t represents the production function, X_0 is a vector of the total distribution of acres in the forest according to their number of years since last regeneration (age),[5] and M_0 is a vector of initial management factors. It will also be necessary to specify a set of initial climatic conditions which have affected each age of trees at time $t = 0$. However, this is not done at this time.

Using matrix notation, Equations (2) and (3) can be represented by a single equation of motion, namely,

$$(18) \qquad X_{t+1} = K\, X_t - B\, U_t\, X_t.$$

Similarly, the management decision equations of motion (4) and (5) can be written as:

---

[5] Last regeneration could have occurred as a result of forest fire.

(19) $M_{t+1} = J\ M_t + e\ W_t.$

In matrix notation, the production function (6) becomes

(20) $V_t = F_t(M_t,\ C_t),$

while the initial values are:

(21) $X_0 = a_0$ and $M_0 = b_0.$

Finally, the requirement that $u_{1t} = 0$ is included directly in the model as the values of the first row and first column in both the B and U_t matrices is set equal to zero.

The benefit function now becomes $B_t(V_t,\ X_t,\ U_t,\ M_t,\ W_t;\ C_t)$. Hence, the problem (8) is reduced to the following:

(22)
$$\max_{U_t, W_t} \sum_{t=0}^{T-1} B_t(V_t,\ X_t,\ U_t,\ M_t,\ W_t;\ C_t)\ \beta^t + \Omega(X_T,\ V_T)\ \beta^T$$
$$\begin{aligned} \text{s.t. } X_{t+1} &= K\ X_t - B\ U_t\ X_t, \\ M_{t+1} &= J\ M_t - e\ W_t, \\ V_t &= F_t(M_t,\ C_t), \\ X_0 &= a_0 \text{ and } M_0 = b_0. \end{aligned}$$

The state variables are X and V, while the control variables are, in essence, U and M.

The Lagrangian associated with this problem is similar to (11):

(23)
$$\begin{aligned} L = &\sum_{t=0}^{T-1} B_t(V_t,\ X_t,\ U_t,\ M_t,\ W_t;\ C_t)\ \beta^t + \Omega(X_T,\ V_T)\ \beta^T \\ &- \lambda_{t+1}\ \beta^{t+1}\ [X_{t+1} - (K\ X_t - B\ U_t\ X_t)] \\ &- \theta_{t+1}\ \beta^{t+1}\ [M_{t+1} - (J\ M_t - e\ W_t)] \\ &- \gamma_{t+1}\ \beta^{t+1}\ [V_t - F_t(M_t,\ C_t)]. \end{aligned}$$

The first-order conditions are as follows:

(24) $(\delta B_t/\delta V_t)\ \beta^t - \gamma_t\ \beta^t;$

(25) $(\delta B_t/\delta X_t)\ \beta^t - \lambda_t\ \beta^t - \lambda_{t+1}\ \beta^{t+1}\ (K - B\ U_t);$

(26) $(\delta B_t/\delta M_t)\ \beta^t - \theta_t\ \beta^t + \theta_{t+1}\ \beta^{t+1}\ J + \gamma_t\ \beta^t\ (\delta F_t/\delta M_t)$;

(27) $(\delta B_t/\delta U_t)\ \beta^t - \lambda_{t+1}\ \beta^{t+1}\ B\ X_t$;

(28) $(\delta B_t/\delta W_t)\ \beta^t + \theta_{t+1}\ \beta^{t+1}\ e$;

(29) $(\delta \Omega/\delta X_T)\ \beta^T - \lambda_T\ \beta^T$; and

(30) $(\delta \Omega/\delta V_T)\ \beta^T - \gamma_T\ \beta^T$.

Setting (24) and (25) equal to zero gives the costate equations:

(31) $\lambda_t = (\delta B_t/\delta X_t) - \lambda_{t+1}\ \beta\ (K - B\ U_t)$, and

(32) $\theta_t = (\delta B_t/\delta M_t) + \theta_{t+1}\ \beta\ J + \gamma_t\ (\delta F_t/\delta M_t)$.

By setting (24) and (30) to zero, the value of $\gamma_t = \delta B_t/\delta V_t$ for $t = 0, \ldots, T-1$ and $\gamma_T = \delta\Omega/\delta V_T$ for T. These values can be substituted into (32) as required.

3.5.1.2 The Leslie Equation

In the foregoing model, the constraints given by Equations (2) through (6) can be written as a Leslie equation, where nonlinearities, stochastic events and so on can be embodied in the Leslie equation. In order to discuss the Leslie approach, we simplify the problem given by Equation (8) and the constraints (2) through (6). Hence, the model is somewhat more general and an extension of similar models employed by economists in fisheries, mining and forestry.

Once again, the objective function to be maximized over all periods of the planning horizon (t = 0, ..., T) is a social benefit function that is discussed in more detail in Section 3.5.2. Denoting the benefit function as B(.), we have the following continuous time problem:

(33) $$\max_u \int_0^T B(V, u, t)\ e^{-\beta t}\ dt,$$

where V(t) represents the volume of usable timber in a given forest stand of age t, u(t) represents the time path of the management decision(s) - the control variable - and β is the discount rate. Problem (33) is maximized subject to a forest-growth constraint and the transversality conditions (i.e. the starting and ending conditions). The growth constraint might be the one employed by Clark (1976:264), namely,

(34) $$dV/dt = g(t)\ f(V),$$

where g(t) is assumed to be a positive decreasing function of t. For example, Kilkki and Vaisanen (1969) employ $g(t) = a\ t^{-b}$, where a and b are determined from physical data; others have used the logistics growth function. As in the Lyon-Sedjo model, research is required to properly specify the benefit function and the growth constraint. Solving the model provides an optimal time path for both the management decision(s) and the volume of usable timber available.

The discrete time counterpart to problem (33), but given a fixed time horizon, is:

(35) $$\max_{u_t} \sum_{t=1}^{T-1} B_t(V_t,\ u_t)\ \beta^t + \Omega\ (V_T)\ \beta^T,$$

where $\Omega(\ )$ is the (salvage) value of the forest at the end of the planning horizon and the remaining variables are as previously defined. Problem (35) is maximized subject to a growth constraint in much the same way as for the continuous time problem. The growth constraint is best represented as a Leslie equation (Leslie 1945, 1948; Pielou 1977:41-57; Usher 1966, 1969, 1972); namely,

(36) $$a_{t+1} = a_t\ A,$$

where a_t is a vector representing the population distribution at time t and

$$A = \begin{bmatrix} F_0 & F_1 & \dots & F_{k-1} & F_k \\ p_{01} & 0 & \dots & 0 & 0 \\ 0 & p_{12} & \dots & 0 & 0 \\ 0 & 0 & \dots & p_{k-1,k} & 0 \end{bmatrix}$$

is the projection or Leslie matrix. The elements of the Leslie matrix are the fecundity parameters for each age group (F_i) located in the first row and the probabilities (p_{ij}) of surviving to the next age group which are located on the lower off-diagonal of the matrix. The importance of the Leslie matrix approach will become evident below.

Methods for solving the discrete time optimal control model are discussed below. The solution consists of a series of management strategies that will maximize the present value of the net benefit or profit function. In this sense, the current methodology is different from that employed by Usher (1966, 1969). While Usher's objective is simply to maximize the growth of a forest, and thereby maximize the annual harvest, our objective is to maximize an economic function such as social welfare.

Risk and uncertainty are missing in the deterministic models of Equation (33), and Equations (35) and (36). Risk refers to events to which a probability can be assigned, while uncertainty refers to unknown, unpredictable events. A particular type of risk (or uncertainty) which needs to be taken into account is that resulting from forest fires. Reed and Clark (1987) include stochastic price and growth in a continuous time optimal control model of the forestry, while Pollard (1966) suggests ways for including stochastic parameters in the Leslie matrix. This can be done, for example, by making the p_{ij} in A stochastic. However, methods for doing this will need to be investigated in the next stage of the study; but, given the importance of risk and uncertainty, we feel that this research will prove worthwhile. What it will provide is an optimal management strategy under conditions of risk and uncertainty.

The Leslie matrix can also be extended to make forest growth nonlinear by adding a functional form within the matrix. Climatic parameters affecting growth can be added,[6] and it appears possible to include the interaction between the forest and insect pests, for example. Further research is required to develop the appropriate Leslie equations, the relationships among all of the state and control variables, and the stochasticity within the system. It will be necessary to use knowledge about the physical and biological characteristics of the ecosystem to determine the functional forms of the mathematical relationships and to estimate the parameters of these equations. However, the advantage of employing the Leslie equation as a constraint is that biophysical scientists are familiar with it. Economists and forest managers, on the other hand, can employ the Leslie equation as a constraint in a discrete time optimal control model. This should benefit and enhance interdisciplinary research.

3.5.1.3 Methods for Solving the Dynamic Problem

Burt and Cummings (1977:16-17) discuss several important points about the use of dynamic models. Firstly, discrete models are important in natural resource economics since the decision mechanism in resource management will of necessity be applied discontinuously with respect to time. Secondly, specification of the decision variables and the appropriate state variables is an important part of model formulation. That is, model specification is important. In this regard, specification of the benefit function is also important, as we demonstrate in the next section. Finally, the equations of motion for natural resources are inherently stochastic. Although we specify a deterministic model, it may be necessary to modify the model to include stochastic elements.

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[6] This would duplicate constraint (6) in the earlier model.

There are a number of different methods for solving the DTOC problem. Some of these methods are considered below.

Gradient Method. One approach to solving this DTOC problem is to employ the gradient technique (Burt and Cummings 1970; Lyon and Sedjo 1983). The Lagrange multipliers λ_t and θ_t are the gradient vectors of U_t and M_t, respectively. That is, λ_t and θ_t are the derivatives of the objective function with respect to the controls U_t and M_t, respectively, at each point in time. Under the gradient method, an initial set of controls is assumed for the entire time horizon. The procedure begins in period T and works its way to the present. Consider the control U and Lagrangian λ. In period T, we know the value of $\lambda_T = \delta\Omega/\delta X_T$ by setting (29) to zero. We also know what the objective functional B_t is for all t, and we know K, B and U_t for all t. Therefore, it is possible to determine the value of λ_{T-1}, λ_{T-1}, and so on from (31) as follows:

$$\lambda_T = \delta\Omega/\delta X_T$$

$$\lambda_{T-1} = (\delta B_{T-1}/\delta X_{T-1}) - \lambda_T \beta (K - B U_{T-1})$$

$$= (\delta B_{T-1}/\delta X_{T-1}) - \delta\Omega/\delta X_T \beta (K - B U_{T-1})$$

$$\lambda_{T-2} = (\delta B_{T-2}/\delta X_{T-2}) - \beta (K - B U_{T-2})[\delta B_{T-1}/\delta X_{T-1} - \delta\Omega/\delta X_T \beta (K - B U_{T-1})]$$

......

In general,

$$(37)\ \lambda_t = \delta B_T/\delta X_t - \sum_{k=t+1}^{T-1} (\delta B_k/\delta X_k) \mathop{\pi}\limits_{j=t}^{k-1} \beta\ (K - B\ U_j) - \delta\Omega/\delta X_T \mathop{\pi}\limits_{j=t}^{T-1} \beta\ (K - B\ U_j).$$

Similarly, for θ_t:[7]

$$(38)\ \theta_t = [\delta B_t/\delta M_t + (\delta B_t/\delta V_t)(\delta F_t/\delta M_t)] + \sum_{k=t+1}^{T-1} [\delta B_k/\delta M_k + (\delta B_k/\delta V_k)(\delta F_k/\delta M_k)] \mathop{\pi}\limits_{j=t}^{k-1} \beta\ J + (\delta\Omega/\delta V_T)\delta F_T/\delta M_T \mathop{\pi}\limits_{j=t}^{T-1} \beta\ J.$$

$$\theta_t = [\delta B_t/\delta M_t + (\delta B_t/\delta V_t)(\delta F_t/\delta M_t)] + \sum_{k=t+1}^{T-1} (t-k+2)\ \beta\ J\ [\delta B_k/\delta M_k + (\delta B_k/\delta V_k)(\delta F_k/\delta M_k)] + (t-T+2)\ \beta\ J\ (\delta\Omega/\delta V_T)(\delta F_T/\delta M_T).$$

Whenever the value of the Lagrangian is positive, this implies that the objective function is increased when the associated control is increased. Likewise, a negative value of the Lagrangian indicates that the associated control for that period should be reduced, while a Lagrangian of zero implies that there should be no change in the associated control for that period. Using the gradient method, the controls are increased, reduced or unchanged by a prespecified amount for each iteration. Thus, the objective function is maximized by this "hill-climbing" approach. An example of the approach, but with no discussion of the mechanism, is provided by Lyon and Sedjo (1983).

Dynamic Programing. Dynamic programing (DP) offers an approach to solving the DTOC problem which is rather straightforward. The DP solution requires that both the state and the control variables be discrete or that intervals for these variables be constructed - that is, neither the state or the control variables can be continuous.[8] If the states and controls take on too many values (or the intervals are too narrow so that there are too many) or there are too many state and control variables, then the so-called "curse of dimensionality" is encountered. Despite this, however, for many practical problems DP is an excellent tool. DP can be used both when the state variables in time t+1 depend upon the state and control variables at time t in a deterministic or stochatic fashion. The DP methodology is discussed by Bellman (1957), Howard (1960), Kilkki and Vaisanen (1969), Burt and Cummings (1970), Buongiorno and Gilless (1987), and others.

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[7] The same relationships could have been obtained for the earlier problem (8), although the expressions would be more complicated as another counter would be involved.

Before discussing this method, however, it is useful to consider substituting (37) into (27) and (38) into (28). Upon doing this, we get relationships similar to (17) and (18) in Burt and Cummings (1970:581). These indicate that the dependence structure in the decision process is Markovian, which then permits the use of DP.

The discrete dynamic optimal control problem (8), (21) or (35) takes into account the fact that decisions (i.e. the choice of control levels) in period t affect the values of the state variables in period t+1 and, hence, the returns that can be earned in future periods - these are appropriately discounted by β. This is unlike single period or static optimization. The principle governing the DP method is Bellman's Principle of Optimality: "An optimal policy has the property that whatever the initial state and decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision" (Bellman 1957:83).

The DP method is as follows. Beginning in period T, we calculate the value of the salvage function for all combinations of the state variables. In period T-1, for every possible set of controls and state variables, the current value of the benefit function, plus the value of the salvage under the various sets of associated controls, is calculated. The controls which maximize this sum for each possible combination of state variables in period T-1 are chosen. Then the procedure is repeated for period T-2, T-3, and so on. Upon reaching the current period, the values of the state variables are observed and the process is reversed to obtain the optimal path.

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[8] In practice, of course, the same is true of the other methods.

In order to get a stationary strategy, it is necessary to assume that the benefit function B(U, M, X, V) is not explicitly a function of time (Burt and Cummings 1970:588).[9] Then the dynamic programing problem can be reduced to a single recursive equation which needs to be solved for period n, where n is the number of years left in the planning horizon. That is, the dynamic programing problem is recursive, and the solution algorithm begins at the end of the multi-stage process in much the same way as the gradient method.

The recursive relationship is as follows:

$$f_0(X, V) = \Omega(X, V)$$

$$f_1(X, V) = \max_{U,M} [\, B(U,M,X,V) + \beta\, f_0(X, V)]$$

$$f_2(X, V) = \max_{U,M} [\, B(U,M,X,V) + \beta\, f_1(KX+BUX, FX-UV)]$$

......

$$f_n(X, V) = \max_{U,M} [\, B(U,M,X,V) + \beta\, f_{n-1}(KX+BUX, FX-UV)].$$

Taking time to be infinite enables convergence to a constant strategy given that the benefit function is invariant.

---

[9] We ignore C and W in the benefit function because W is included in M, while C goes into the determination of V.

Approximation Method. Burt and Cummings (1970 and 1977) also suggest the use of an approximation procedure to solve DTOC problems. The advantage of this method is that it is simpler than either the DP or gradient method, but it requires that the real world falls into the region of approximation. Burt (1964) shows that this is indeed the case for a groundwater problem and for soil conservation in the Palouse region of eastern Washington and western Idaho.

3.5.2 Appropriate Measures of Welfare: Specifying the Objective Function

In this section, we employ a partial equilibrium analysis to study the economics of climatic change impacts on the Canadian boreal forest. Thus, we assume that there are no distortions in other, affected markets - that is, we assume perfect competition with no externalities.[10] Kokoski and Smith (1987) investigate the validity of partial equilibrium measures of economic welfare in the case of climatic changes. Their results indicate that partial equilibrium welfare measures offer a reasonable approximation to the true welfare measures, obtained from a computable general equilibrium model (see Shoven and Whalley 1984), in cases where the exogenous change is large. However, in the current study, we do not know if the change in climate as it affects the boreal forest is a sufficiently large change; hence, it will likely be necessary to repeat the Kokoski and Smith experiment to determine the validity of the partial equilibrium assumption.

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[10] Simply put, externality refers to pollution (e.g. acid rain), scenic amenities, nonmarket uses of forest lands (e.g. hunting) and so on. Clearly, the assumption of perfect competition holds only as an approximation.

In applied welfare economics and, therefore, in analyzing the economic benefits of climatic change upon the boreal forest, it is important to determine the appropriate measure of benefits and costs - the correct welfare measure. This welfare measure subsequently becomes the objective function in an optimal control model. Lyon and Sedjo (1983) employ the sum of the welfares of consumers and producers as their measure of net benefit; these are the concepts of consumer and producer surplus, respectively, and they are illustrated in Figure 2.8. The impact of a change in climate can be illustrated in Figure 3.1 by an outward shift of the supply curve. If the climatic change causes an increase in the supply of commercial timber, then the shaded area between S and S′ (the new supply curve) is a measure of the welfare gain or net benefit from climate change per period of time (Lovell and Smith 1985).

In the framework of Figure 3.1, the objective of the social decision maker is to maximize the present value of future producer plus consumer surpluses; that is, the objective is to maximize the discounted sum of surpluses. The measure of surplus for each time period can be written mathematically as:

$$(39) \qquad s_t = \int_0^{V_t} [D_t(q) - S_t(q,M,C,\gamma)]\, dq,$$

where s_t is the consumer plus producer surplus in year t;

V_t is the volume of commercial timber marketed under perfectly competitive conditions in year t;

$D_t(\ )$ is the demand function for timber in year t; and

$S_t(\ )$ is the supply function for timber in year t.

The supply of timber is a function of the volume of timber available, previous management decisions regarding regeneration (M), climate (C) and other parameters (γ) such as the costs of harvesting. Notice that the measure of surplus in (39) is not the same as private surplus, which would be equal to gross revenues minus costs; that is,

$$\text{private surplus in year } t = P_t\, V_t - \int_0^{V_t} (q,.)dq$$

$$= \text{producer surplus},$$

where P_t is the per unit price of commercial timber at time t.

In order to determine the benefit of a change in climatic conditions, the discounted surplus under the original climate conditions needs to be subtracted from the discounted surplus under the new climatic conditions. That is, the economic problem is to maximize the discounted net value of the objective given by (39) over time, subject to a number of dynamic constraints, including a forest growth constraint. One then compares the net present value of benefits under the optimal decision path for the original situation with the net discounted benefits under the optimal path for the alternative climatic conditions. This requires an optimal control model (see Bowes and Krutilla 1985; Reed 1986).

The situation depicted in Figure 3.1 and the measure of producer plus consumer surpluses (area abc) is valid only in a closed economy. As Canada exports in excess of 50% of its timber and timber products, the model in Figure 3.1 is not valid, nor is the welfare measure represented there. Rather, an international trade model is required. In Figure 3.2, it is assumed that Canada is a timber surplus region, while the United States is a timber deficit region. As in similar models, transportation costs are ignored, not because they are

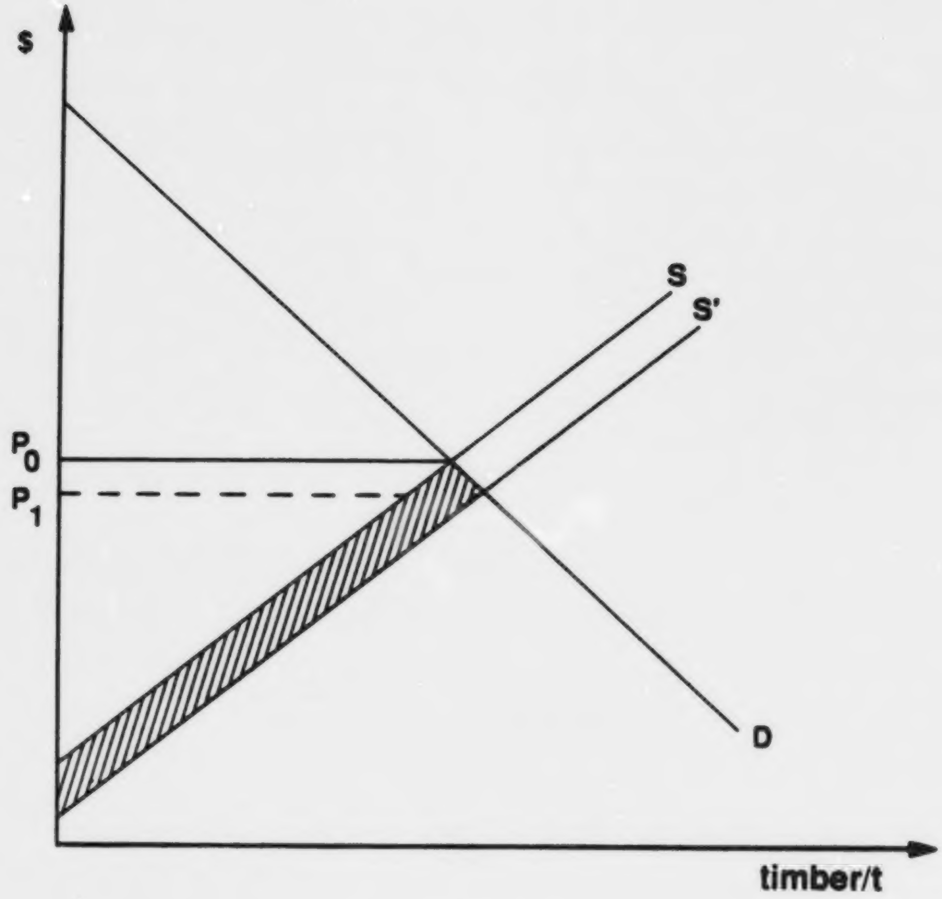
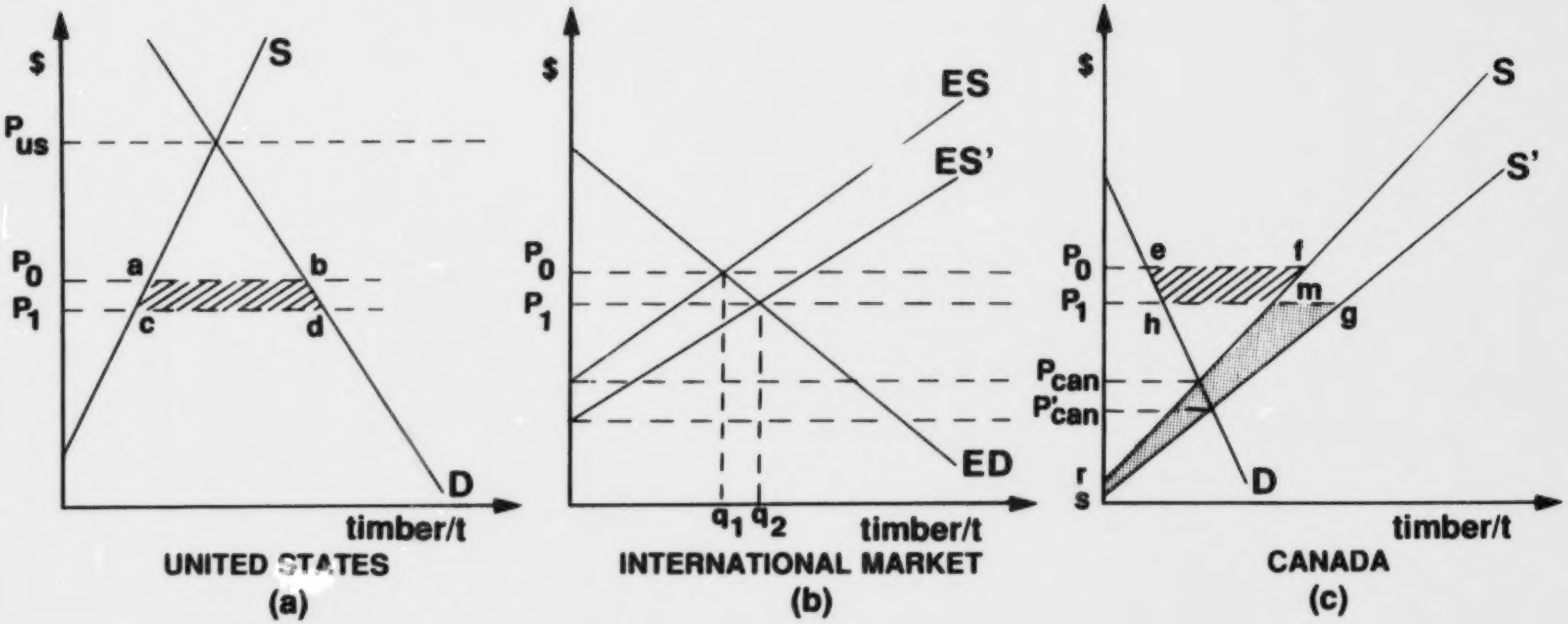


Figure 3.1 Welfare Change Per Unit of Time.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D
timber/t

UNITED STATES
(a)

INTERNATIONAL MARKET
(b)

CANADA
(c)

Figure 3.2 Benefits of Climatic Change in an Open Economy.

unimportant, but because their inclusion does not change the basic analysis. Under free trade and before the impact of the climatic change, Canada exports an amount Oq_1 of timber to the U.S. The domestic price in Canada is higher under free trade than it would be in the absence of trade ($P_{CAN} < P^0$), while the opposite is true in the U.S.

The shift in Canada's supply of timber from S to S′, due to a change in climate, causes the excess supply curve (Figure 3.2(b)) to shift from ES to ES′. The free trade price drops from P_0 to P_1 and the quantity of timber traded increases to Oq_2. In Figure 3.2(a), we find that there is a loss to U.S. producers equal to area (P_0acP_1), but U.S. consumers gain area (P_0bdP_1). The net gain to the U.S. from a climatic change which affects only the Canadian boreal forest and not U.S. forests is given by area (abcd) in Figure 3.2(a). Canadian consumers also experience a gain in welfare which is measured by area (P_0ehP_1) in Figure 3.2(c). Before the change in climate, Canadian timber producers earned a surplus given by area (rP_0f) in Figure 3.2(c); after the climatic change the producer surplus is measured by area (sP_1g). The change in the welfare of Canadian producers is, therefore, area (srmg - P_1P_0fm) in Figure 3.2(c). The net gain to Canada is given by area (srmg - efmh) or the fully shaded area minus the partially shaded area. Without knowing the elasticities of supply and demand and the extent of the supply shift, it is not clear whether Canada experiences a net gain or loss on account of a climatic change. It is clear, however, that the U.S. will be a net gainer of a change in climate whose only effect is to increase the productivity of Canada's boreal forests.

It is also necessary to take into account trade distortion. The U.S. government threatened to levy a countervail duty on Canadian exports of timber products (i.e. softwood lumber) as these were, apparently, being subsidized.[11] In response, the Canadian government offered to impose voluntary restraints, and these were accepted by U.S. authorities. Boyd and Krutilla (1987) estimate that the welfare loss to Canada would be $78.6 million if the U.S. imposes a 10% ad valorem tax; about $5 million would be lost in the current study region.[12] However, under voluntary restraints which reduce U.S. imports from Canada by the same amount, Canada would gain $99.2 million, and the gain to the study region would be $6.2 million. Since the actual restraints imposed by Canada exceeded the estimates by Boyd and Krutilla (1987), the gain to Canada was even larger.

Imposition of a countervail duty by the U.S. or voluntary restraint by Canada lowers the Canadian domestic price, but increases the price in the U.S. (Figure 3.3). The amount traded is given by distance ab in Figure 3.3(a), which is equal to distance sr in Figure 3.3(b). In Figure 3.3, the free trade price is P_0, while the price under trade distortion is P_1. Imposition of a countervail duty by the U.S. results in a welfare gain by U.S. producers, but an even greater loss to U.S. consumers of timber products. The gain to U.S. producers is area ($P_1'afP_0$) in Figure 3.3(a), while the welfare loss to consumers is $P_1'bcP_0$. Since the government collects area (abde) in Figure 3.3(a) plus area (mnrs) in Figure 3.3(b) as revenue, the net welfare gain to the U.S. is given by area (mnrs) in Figure 3.3(b) minus the shaded triangles (aef + bcd) in Figure 3.3(a). The net welfare loss in Canada is given

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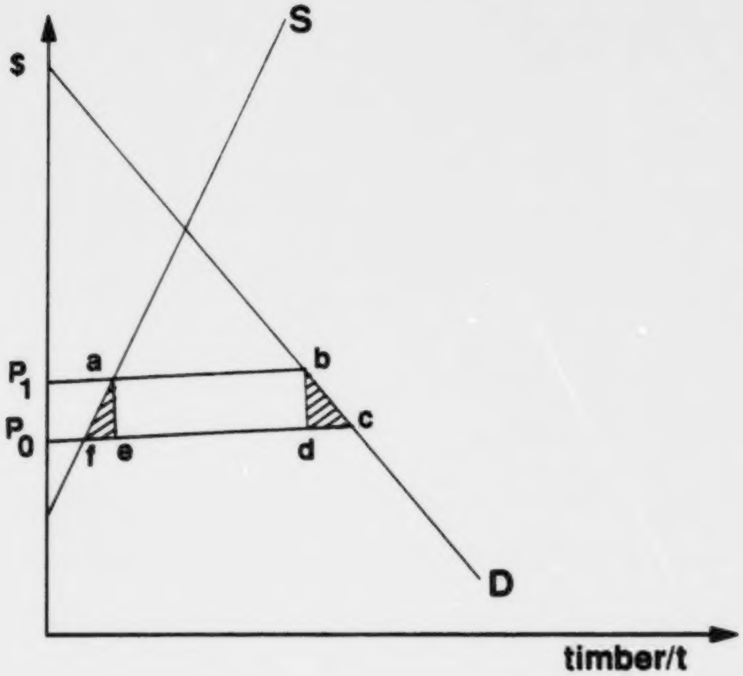
[11] It is extremely difficult to determine the extent of subsidy in these cases. For a discussion in a natural resource context see Schmitz et al. (1981).

[12] This assumes an elasticity of supply of 0.89.


$
S
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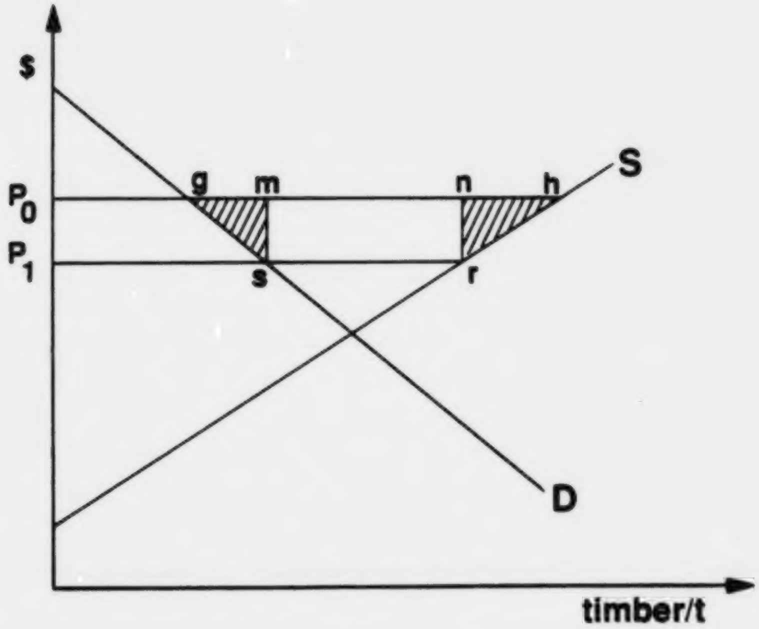
D
timber/t

UNITED STATES
(a)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CANADA
(b)

Figure 3.3 Welfare Gains and Losses with Trade Distortion.

by area (ghrs) in Figure 3.3(b).

If Canada is able to impose an export tax on Canadian producers (voluntary quotas or increased stumpage fees), the loss to the U.S. is measured by area (abcf) in Figure 3.3(a). Canadian consumers gain area (P_0gsP_1) and producers lose P_0hrP_1 in Figure 3.3(b), but the government collects area (mnrs) in Figure 3.3(b) plus area (abde) in Figure 3.3(a) as revenue. The net gain to Canada is given by area (abde) in Figure 3.3(a) minus the shaded areas in Figure 3.3(b). Regardless of how the trade distortion comes about, the total loss in international welfare is given by the sum of the shaded areas in Figure 3.3(a) and (b). Interestingly, the welfare impacts of a change in climate that affects only the boreal forests of Canada will be similar to those illustrated in Figure 3.2. However, their magnitude will not be the same since the starting and ending prices, which are the trade distorted prices, are different.

Finally, it is possible to examine the welfare impacts when climatic changes affect both the Canadian boreal forest and forests in the United States. The foregoing model can be used to examine situations where climatic changes (1) cause U.S. forest growth to be proportionally smaller than that in Canada, (2) cause greater proportional growth in the U.S. than in Canada, or (3) cause a reduction in U.S. forest productivity, but an increase in the productivity of the Canadian boreal forest.[13] In Figure 3.4, we illustrate only the case where there is an increase in the productivity of both the U.S. and

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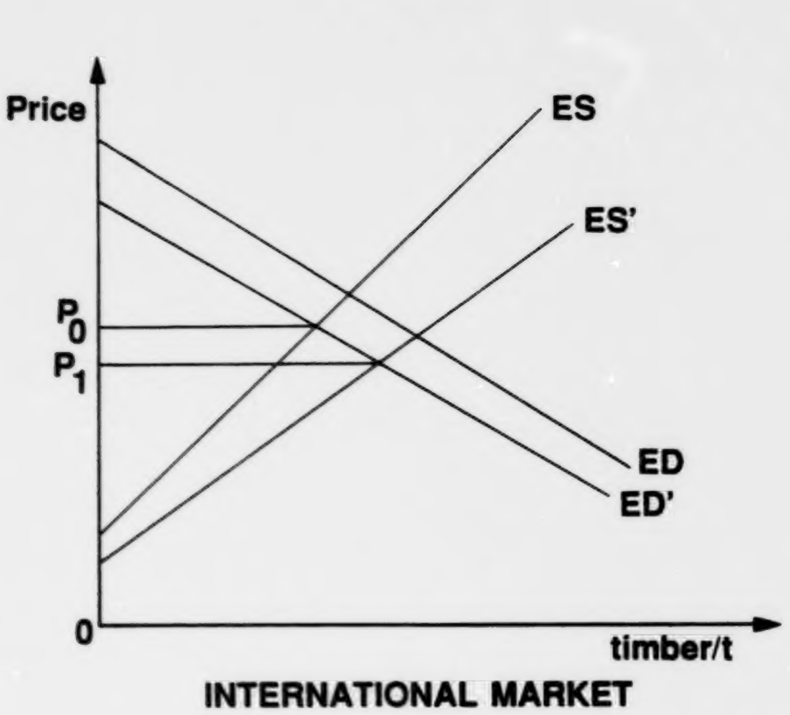
[13] The role of the B.C. coastal forest and other forests in other parts of the world has been ignored. However, the framework employed in the text can easily be extended to handle these cases; only the complexity of the analysis increases.



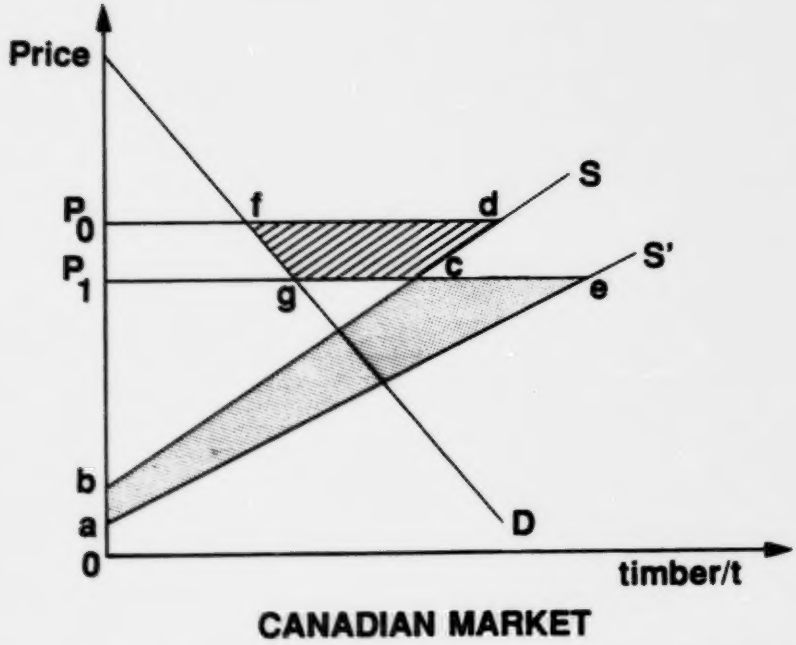


Figure 3.4 Welfare Gains and Losses When Climatic Change Increases the Available Timber in Both Canada and the U.S.

Canadian forests.

Only two panels of the trade diagram of Figure 3.2 are shown in Figure 3.4, namely, the international market (Figure 3.4(a)) and the Canadian market (Figure 3.4(b)). As Canada is a surplus timber producing region, an increase in the supply of available timber due to climatic changes will shift the supply in the domestic market to the right - from S to S′. With fixed demand, this will result in an outward shift of the excess supply curve in the international market from ES to ES′. The increase in the supply of U.S. timber will result in a reduction of excess demand from ED to ED′ in Figure 3.4(a) since the U.S. is a timber deficit region. As before, it is a simple matter to demonstrate that U.S. consumers gain more than U.S. producers could possibly lose. The net gain to Canada is given by area (cdfg - abce) in Figure 3.4(b), the fully shaded area minus the partially shaded area. Again it is clear that, without knowledge of the elasticities of supply and demand in the trading countries and the magnitude of the supply shifts, it is not possible to determine whether Canada is a net gainer or loser as a result of climatic change.

In conclusion, the foregoing analysis points out the difficulty of constructing the objective (net benefit) function to employ in an analysis of the economic benefits of climatic change on the boreal forest in Canada. It is apparent that one cannot simply employ the function used by Lyon and Sedjo (1983) as this does not take into account international trade, which will undoubtedly change the conclusions about the economic benefits of climatic change. Further, trade considerations enter into an analysis of secondary impacts on the economy. It is clear from Figures 3.2 and 3.4 that it is not possible to determine whether an increase in the supply of available commercial timber in Canada will lead to an overall benefit or loss to Canada, or whether there will even be an increase in timber output. Without proper specification of the objective function, therefore, it is misleading to calculate increases in economic activity by a methodology such as I-O analysis. It is important in the first instance to determine whether or not the net benefits to Canada are positive.

Finally, it is important to recognize the impacts of government policies such as countervail duties, voluntary quotas, and so on. Removal of these at some future date, perhaps as a result of a Canada/U.S. free trade agreement, or imposition of additional trade restrictions, perhaps as a result of increased U.S. protectionism, will lead to welfare impacts which could be more significant than those occurring as a result of climatic changes.

3.5.3 Nonmarket Values: Forest Functions not Traded in the Market

The focus of the preceding discussion, and probably the focus of the larger study as well, is on commercial timber value and the economic benefits which might arise if favorable climatic changes increase available timber volume. But social and private net benefits diverge in the case where forest lands have value in uses other than commercial timber.[14] As with many forest lands, the western boreal forest has value as a scenic amenity, as a recreational resource (backpacking, hunting, fishing, wilderness experience, etc.), as wildlife habitat, as a watershed, and as a global regulator of weather and pollution. Each of these functions, as well as its value as commercial timber, is affected by climatic changes which impact on forest growth.

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[14] This is an example of a distortion as discussed previously.

Where multiple uses exist, these uses can be conflicting or complementary. The existence of multiple uses simply implies a more complicated management strategy; however, the forest must be managed in such a way as to attain the greatest possible net benefit to society. This implies that the benefit function of Section 3.5.1 must be modified still further. While the objective of greatest social value may be difficult to achieve, management strategies which ignore the multiple use nature of the forest lands are simply inefficient from an economic perspective. The forest manager can affect vegetation cover and its development through various management practices. These practices include harvesting, timing and type of thinning, spraying for insect pests, regeneration decisions, access restrictions, and trail and facility construction. The choice of strategies depends upon the objectives of the forest manager. As indicated above, if management is for multiple use, then the strategy will be different than it would be if managers only respond to market data.

In order to manage the forest for multiple uses, it is necessary to modify the benefit function in equations (8) and (33) to take into account "products and services of the forest which, in addition to harvested timber, include water storage, wildlife, grazing and recreational and amenity services that depend on the condition of the standing vegetation" (Crocker 1985:244). Including these considerations expands the number of control variables required in the model. Access restrictions, trail and facility construction, and other management activities will be added to existing controls. However, this only expands the size of the problem, but not the basic methodology.

The major problem to be addressed when multiple uses are considered is that of valuing these uses. Unlike timber value, which can be determined in the market place, wildlife, water storage, scenic and other values are not determined in the market. These nonmarket values can, however, be ascertained using a number of techniques which are now becoming familiar to practising economists. The major tool used in this valuation of nonmarket goods is known as contingent valuation (Cummings et al. 1986), although the travel cost method (and variations of it) remain useful in analyzing recreation values.

The value of forest lands in domestic grazing can be determined from market data; but the value of wildlife habitat is more difficult to estimate. Methods for determining the values of wildlife species to hunters (e.g. duck, elk, moose) and for evaluating recreational activities (e.g. backpacking, camping, swimming, canoeing) are well-known and can be applied quite easily to the study region - the western boreal forest. However, to do these types of studies will require conducting surveys of hunters and recreationists. Although the importance of the boreal forest as a source of recreational activity and wildlife habitat cannot be overlooked, it is also necessary to conduct research into suitable and usable methods for determining the value of scenic amenities and the value of the condition of a forest stand. Methods for determining these values have been pioneered by Arthur (1977), Crocker (1985), Brown and Daniel (1986), and others.[15]

For the current study, however, it is important to recognize that the forest also provides preservation benefits which economists are now finding can be quite substantial (Greenley et al. 1981). For example, Greenley, Walsh and Young found that a reduction in water quality in the South Platte River basin of Colorado due to increased mining activity resulted in a welfare loss of $61 million per year to residents in Colorado. Therefore, ignoring the preservation values in the management of western Canada's boreal forest could result in a substantial misallocation of resources; in particular, it results in improper use of forest lands.

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[15] For example, Crocker found that a reduction in the condition of the San Bernadino National Forest in California due to pollution resulted in an annual loss of $2 per user day.

Preservation value includes option, bequest and existence demands. Option demand is the amount of money which an individual who anticipates visiting a forest would pay to guarantee future access to the forest, even though he is uncertain as to whether he may, in fact, make such a visit. Methods for determining option value have been developed (Freeman 1984; Walsh et al. 1984; Cory and Saliba 1987; Fisher and Hanemann 1986), but further work into the method for empirical implementation is required. "Bequest value is defined as the willingness to pay for the satisfaction derived from endowing future generations with a natural environment" (Greenley et al. 1981:657). Existence value is the amount a person is willing to pay for the knowledge that a natural environment such as a forest is preserved in a particular state. Existence value may be particularly important in the current study.

Finally, given the vastness of Canada's western boreal forest, it is necessary to consider its function in ameliorating global pollution - its function as a global waste receptor. If climatic change causes an increase in biomass, the pollution absorption capacity of the forest would increase. The economic value of the change in climate is equal to the value placed on this added capacity to absorb pollution. It is the sum of individuals' willingness-to-pay, not only in Canada, but globally.

Since Canada's boreal forest constitutes one of the largest forest areas and large tracts of it are still in virgin condition, an important consideration is preservation demand, particularly existence demand. No studies have been conducted to determine the existence value of the boreal forest. Indeed, to our knowledge, there are no theoretical or empirical studies regarding the existence value of any resource.[16] Nor has there has been any research to determine the economic value of the global weather regulator, pollution absorption and water storage functions of the boreal forest, or for that matter any forest. It is also necessary to determine how changes in climate affect these functions and what the economic value of such changes might be. There is an opportunity to develop theoretical and empirical methods which will enable Canada to better manage its vast forest regions for multiple use. It may even be possible to convince those in other countries to contribute to this management.

3.6 Designing the Climatic Change Impact System and the Use of System Analysis

Systems analysis is a useful approach in the case of an interdisciplinary study on the effects of a change in the environment, such as the climate, on another component like the forest (first order impact). This affects the forest industry, other forest related sectors and the economics of these sectors on local, national and international levels (second order impacts). It has been used in climate impact assessment (e.g. Parry et al. 1987) and in ecology (e.g. Rosswall 1971). It is especially effective for interdisciplinary studies, as it provides an overview of how the different models and/or concepts fit together and relate to one another in a conceptual framework. This is provided by developing a flow diagram of the system. Iterative feedback processes and system analytical techniques such as frequency and sensitivity analysis can be used. Systems analysis can provide a research framework for creating, testing and improving mathematical and conceptual sets of interactive models.

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[16] Greenley, Walsh and Young only considered option demand.

A preliminary climate change-forest-economics system diagram was developed for this study and is shown in Figure 3.5 as an example of a systems approach. The main models, impacts, and feedback loops are sketched in the diagram. The results from each model are input to downstream models, finally leading to estimates of changes in economic welfare. A change in economic welfare would in turn be affected by policy changes.

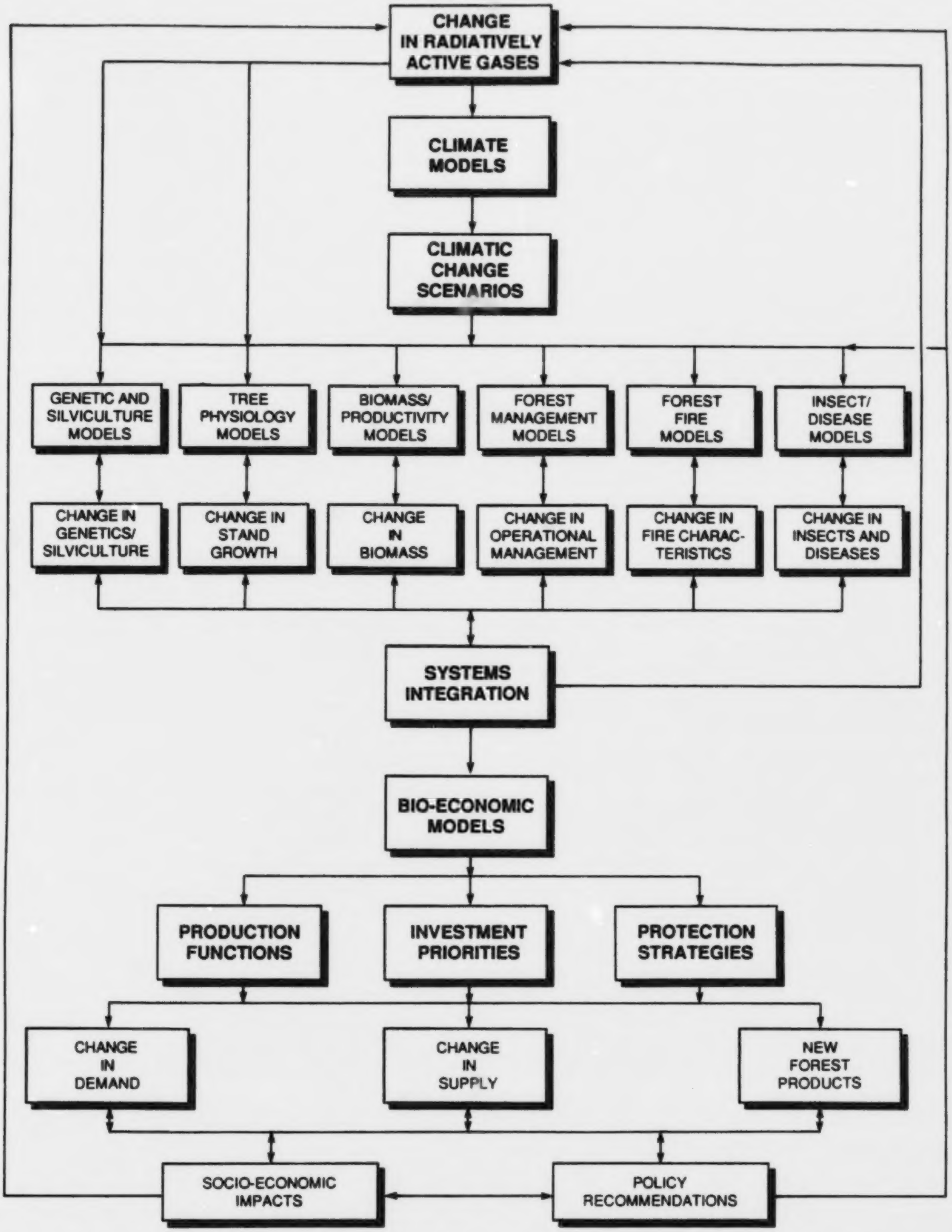

CHANGE IN RADIATIVELY ACTIVE GASES
CLIMATE MODELS
CLIMATIC CHANGE SCENARIOS
GENETIC AND SILVICULTURE MODELS
TREE PHYSIOLOGY MODELS
BIOMASS/ PRODUCTIVITY MODELS
FOREST MANAGEMENT MODELS
FOREST FIRE MODELS
INSECT/ DISEASE MODELS
CHANGE IN GENETICS/ SILVICULTURE
CHANGE IN STAND GROWTH
CHANGE IN BIOMASS
CHANGE IN OPERATIONAL MANAGEMENT
CHANGE IN FIRE CHARAC- TERISTICS
CHANGE IN INSECTS AND DISEASES
SYSTEMS INTEGRATION
BIO-ECONOMIC MODELS
PRODUCTION FUNCTIONS
INVESTMENT PRIORITIES
PROTECTION STRATEGIES
CHANGE IN DEMAND
CHANGE IN SUPPLY
NEW FOREST PRODUCTS
SOCIO-ECONOMIC IMPACTS
POLICY RECOMMENDATIONS

Figure 3.5 System Illustrating Climatic Change/Forest/Economic Interactions.
Note: Market Model should be termed Economic Model when nonmarket effects are considered.

4 RESULTS AND DISCUSSION

4.1 Climatic Change Scenarios

In Chapter 3, several climatic change scenarios were selected and developed as based on the GISS and GFDL General Circulation Model results (termed GISS1, GISS2, GFDL1 and GFDL2). A comparison for the scenarios is the historical climatic data, that is the 1951 to 1980 normals (termed HIST).

The climatic change scenario and historical data are provided for gridpoint locations. The scenarios based on GISS have gridpoint sizes of 4° latitude by 5° longitude, and the gridpoint sizes for the GFDL-based scenarios have grid sizes of approximately 4.45° latitude by 7.5° longitude. Historical climatic data were provided for these gridpoint locations from the Canadian Climate Centre (Street, pers. comm.).

Four gridpoints from each of the GISS-based and GFDL-based scenarios were selected to represent the three main forest zones for some of the analysis, especially those requiring much data. Five gridpoints are in the predominately forest zone, two are in the forest-grassland transition zone, and one is in the forest tundra transition zone (Figure 1.1). These points are assumed representative of the grid area and thus of a large portion of a forest zone and not necessarily of that point. The results of all of the impact models should be provided for all the available gridpoint locations in future studies once the appropriate impact models are selected.

The basic characteristics of the temperature and precipitation of the climatic change scenarios for CO_2 doubling are briefly described in this section in order to provide a foundation for examining the results of the climatic indices or models that are based on the temperature and precipitation data. The characteristics of the temperature and precipitation data are displayed through time and space (Appendix C).

Temperature and precipitation of the GISS- and GFDL-based scenarios are examined by means of graphs of the seasonal distribution of the monthly means for the representative gridpoints, and of maps of the spatial pattern across the study area for all available gridpoint locations within, as well as just outside the study area, for sake of characterizing the boundary conditions.

Climatologists conventionally divide the year into four equal seasons for the purposes of description. Summer is considered to be June, July and August; fall is September, October and November; winter is December, January and February; and spring is March, April and May. The middle month of each season is considered representative of each season's established characteristics. These conventions are used in this study.

4.1.1 Temperature Characteristics Depicted by the Climatic Change Scenarios

The seasonal distribution of the climatic scenarios is examined by means of plotting the mean temperatures against time in months for the eight representative points mentioned previously (Figures C.1 to C.2, Appendix C). The most noticeable characteristic of the graphs is that the lowest increments above normal are projected for the summer months for both scenarios. A difference noticed is that while GISS results depict the greatest increments for the winter months (often in December) at about 6° to 9°C, the largest GFDL increments are for the spring months (often in April) and are about 6° to 7°C. Also, the GISS temperature increments depict a more uniform change from month to month, while the GFDL month-to-month changes are much more erratic.

A result of the lower increase in temperatures during the summer months as compared to the winter months would be that the winter to summer change would not be quite as drastic. Continentality can be measured by the difference between the average temperature of the warmest and coldest months and by the latitude of the location. Thus the climatic change scenarios depict a climate that is less continental than the current climate of the study area.

Maps of isotherms for the key months of each season and for each of the two main climatic scenarios are used to explore spatial distributions (Figures C.3 to C.4, Appendix C). An obvious difference between scenarios is that the increments above normal are greater with the GISS- than the GFDL-based scenario, especially in winter.

4.1.2 Precipitation Characteristics Depicted by the Climatic Scenarios

As for temperature, seasonal and spatial patterns of the precipitation climate are characterized with the aid of graphs and maps (Figures C.5 to C.8, Appendix C).

Again, as for temperature, the seasonal distribution of the mean monthly precipitation amounts for the GISS1 scenario is more uniform than for the GFDL1 scenario. The month of maximum precipitation does not change with the projected climatic changes, but continues to be July for much of the study area, except for the far south and the far north which have June and August maxima.

However, the amount of precipitation is expected to change with CO_2-induced climatic change as described by these scenarios. In general, both of the scenarios show an increase in precipitation for most months. Exceptions exist, with both scenarios having decreases of precipitation, especially in the fall for GISS1 and during both summer and fall for the GFDL1 scenario. The GFDL1 scenario has the greatest ratios of change, both as increases and decreases, as compared to the GISS-based scenario. Again, as for temperature, GISS1 has a much more uniform precipitation climate than GFDL1.

Maps of the isohyets can be used to explore and compare spatial patterns for the GISS1 and GFD1 climatic scenarios (Figures C.7 and C.8, Appendix C).

4.2 Effects of Climatic Change on Climatic Resources for Forestry

As discussed previously, several indices and/or models were used to analyze the impacts of the climatic change scenarios on the thermal climate (growing degree-days), the moisture climate (precipitation effectiveness), and the combined thermal-moisture effects (climatic index of agricultural potential which reflects biomass potential). Results are presented in Table 4.1 for each of these indices/models for each climatic change scenario. Eight gridpoint locations are used as discussed in Section 4.1 and shown in Figure 1.1.

Growing degree-day (GDD) results indicate an increase of 35 to 48% for the GISS scenario representative gridpoints and 13 to 40% for the GFDL representative gridpoints higher than normal GDDs. To provide an idea of the implications, the thermal resources for forestry at location B in the predominately forest zone becomes 1,829 GDD with the GISS scenario. This value is similar to that of locations in North Dakota, for example. A similar location for the GFDL scenario would have GDD amounts similar to those of the southern Saskatchewan. If the growing

TABLE 4.1

Impact Model Results Implied by Several Climatic Change Scenarios for Selected Locations in the Boreal Forest[a]

	Location A (58° 00'N 110° 00'W)			Location B (54° 00'N 105° 00'W)		
	Scenario					
	HIST	GISS1	GISS2[b]	HIST	GISS1	GISS2
	(1951-80)	(2xCO$_2$TP)[c]	(2xCO$_2$T)	(1951-80)	(2xCO$_2$TP)[c]	(2xCO$_2$T)
GROWING DEGREE-DAYS (GDD)	1170	1579 (+35%)	1579 (+35%)	1235	1829 (+48%)	1829 (+48%)
PRECIPITATION EFFECTIVENESS INDEX (I)	51.6	63.0 (+22%)	46.6 (-10%)	46.0	51.6 (+12%)	41.4 (-10%)
DRYNESS FACTOR (Fs)	5.6	6.8 (+21%)	5.8 (+4%)	5.7	5.0 (-12%)	4.5 (-21%)
HELIOTHERMIC FACTOR (HT)	19.7	28.3 (+44%)	28.3 (+44%)	24.0	32.0 (+33%)	32.0 (+33%)
BIOMASS POTENTIAL (CA)	17.0	26.8 (+58%)	19.9 (+17%)	16.0	19.1 (+19%)	15.7 (-2%)

	Location C (58° 00'N 120° 00'W)			Location D (50° 00'N 100° 00'W)		
	HIST	GISS1	GISS2	HIST	GISS1	GISS2
GROWING DEGREE-DAYS (GDD)	995	1384 (+39%)	1384 (+39%)	1500	2075 (+38%)	2075 (+38%)
PRECIPITATION EFFECTIVENESS INDEX (I)	50.8	60.3 (+19%)	46.7 (-8%)	45.4	46.8 (+3%)	40.5 (-11%)
DRYNESS FACTOR (Fs)	7.0	6.8 (-3%)	5.8 (-17%)	5.2	5.4 (+4%)	5.1 (-2%)
HELIOTHERMIC FACTOR (HT)	17.4	26.8 (+54%)	26.8 (+54%)	28.1	34.0 (+21%)	34.0 (+21%)
BIOMASS POTENTIAL (CA)	17.4	26.6 (+53%)	22.1 (+27%)	18.5	18.7 (+1%)	16.3 (-12%)

TABLE 4.1 (Continued)

	Location E (64° 24'N 120° 00'W)			Location F (55° 30'N 105° 00'W)		
	HIST	GFDL1	GFDL2	HIST	GFDL1	GFDL2
	(1951-80)	(2xCO$_2$TP)[c]	(2xCO$_2$T)	(1951-80)	(2xCO$_2$TP)[c]	(2xCO$_2$T
GROWING DEGREE-DAYS (GDD)	887	1239 (+40%)	1239 (+40%)	1111	1452 (+31%)	1452 (+31%)
PRECIPITATION EFFECTIVENESS INDEX (I)	33.3	31.2 (-6%)	30.8 (-8%)	50.0	58.1 (+16%)	46.5 (-7%)
DRYNESS FACTOR (Fs)	3.6	2.6 (-28%)	2.6 (-28%)	4.8	5.7 (+19%)	5.0 (+4%)
HELIOTHERMIC FACTOR (HT)	16.9	24.4 (+44%)	24.4 (+44%)	21.5	27.0 (+26%)	27.0 (+26%)
BIOMASS POTENTIAL (CA)	8.6	10.5 (+22%)	9.7 (+13%)	13.6	18.9 (+39%)	14.3 (+5%)

	Location G (59° 54'N 120° 00'W)			Location H (51° 06'N 112° 30'W)		
	HIST	GFDL1	GFDL2	HIST	GFDL1	GFDL2
	(1951-80)	(2xCO$_2$TP)[c]	(2xCO$_2$T)	(1951-80)	(2xCO$_2$TP)[c]	(2xCO$_2$T
GROWING DEGREE-DAYS (GDD)	1140	1531 (+34%)	1531 (+34%)	1521	1718 (+13%)	1718 (+13%)
PRECIPITATION EFFECTIVENESS INDEX (I)	42.3	44.7 (+6%)	38.4 (-9%)	33.3	39.1 (+17%)	30.8 (-8%)
DRYNESS FACTOR (Fs)	4.9	5.4 (+10%)	4.7 (-4%)	4.1	4.2 (+2%)	3.1 (-24%)
HELIOTHERMIC FACTOR (HT)	18.5	28.7 (+55%)	28.7 (+55%)	20.8	30.4 (+46%)	30.4 (+46%)
BIOMASS POTENTIAL (CA)	12.6	18.4 (+46%)	14.3 (+13%)	7.7	16.8 (+118%)	11.1 (+44%

[a] Values in brackets are the percentage increases or decreases in relation to the mean climatic values for the 1951 to 1980 standard period (HIST). Locations are shown in Figure 1.1.

[b] Scenarios GISS2 and GFDL2 use normal precipitation means.

[c] T and P stand for temperature and precipitation.

season thermal resources on a long-term basis increased to the levels indicated by **either** of these climatic change scenarios, the climate may be more suitable for grassland vegetation for a large portion of the study area. The implications of these potential changes for forest species, zones and forestry are important and should be further explored for the study area.

Using the 600 and 1,300 GDD isolines as delimiters of the northern and southern boundaries of the boreal forest as Kauppi and Posch (1985) have done, one can estimate the shift in position of the zone as the forest adapts to climatic change. Both scenarios show considerable shifts in the forest zones using the above relationship with the GISS scenario producing the greatest shifts because of the higher temperatures (Table 4.2, Figures 4.1 and 4.2). GDD for the normal climatic period (HIST) are shown for comparison in Figure 4.3.

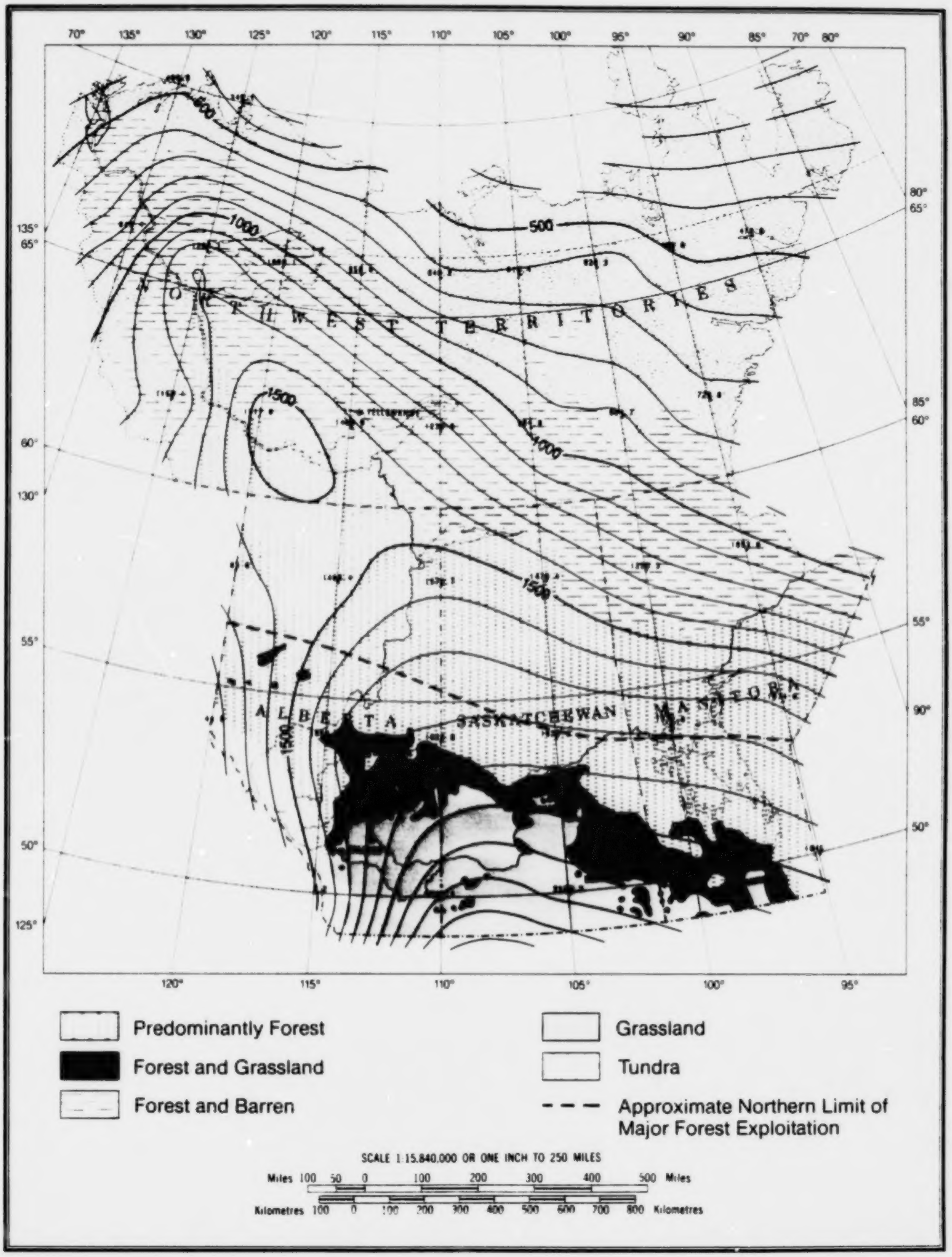
The GISS scenario shows a northward shift of the northern limit of the boreal forest, as indicated by the 600 GDD, isoline by about 80 to 720 km northward in the study area (Table 4.2). The southern boundary of the boreal forest, as delimited by the 1,300 GDD isoline, shifts northward of its current position about 470 to 920 km.

The GFDL scenario suggests that the northward shift in the northern boundary of the boreal forest would be about 100 to 700 km. The northward shift of the southern limit of the boreal forest is estimated to range from about 250 to 900 km.

The northern limit of major forest exploitation is a boundary of importance in forestry. It is located in the predominantly forest zone and its approximate location is shown on Figure 1.1. If it shifts along with the northern and southern boundaries of the boreal forest, then its

Table 4.2. Shift (km) in the Northern and Southern Boundaries of the Boreal Forest (delimited by the 600 and 1,300 growing degree-day isolines) as Implied by the GISS- and GFDL-based Climatic Change Scenarios.

Forest Boundary	Climatic Change Scenario	
	GISS	GFDL
Northern	80 to 720	100 to 730
Southern	470 to 920	250 to 900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85°
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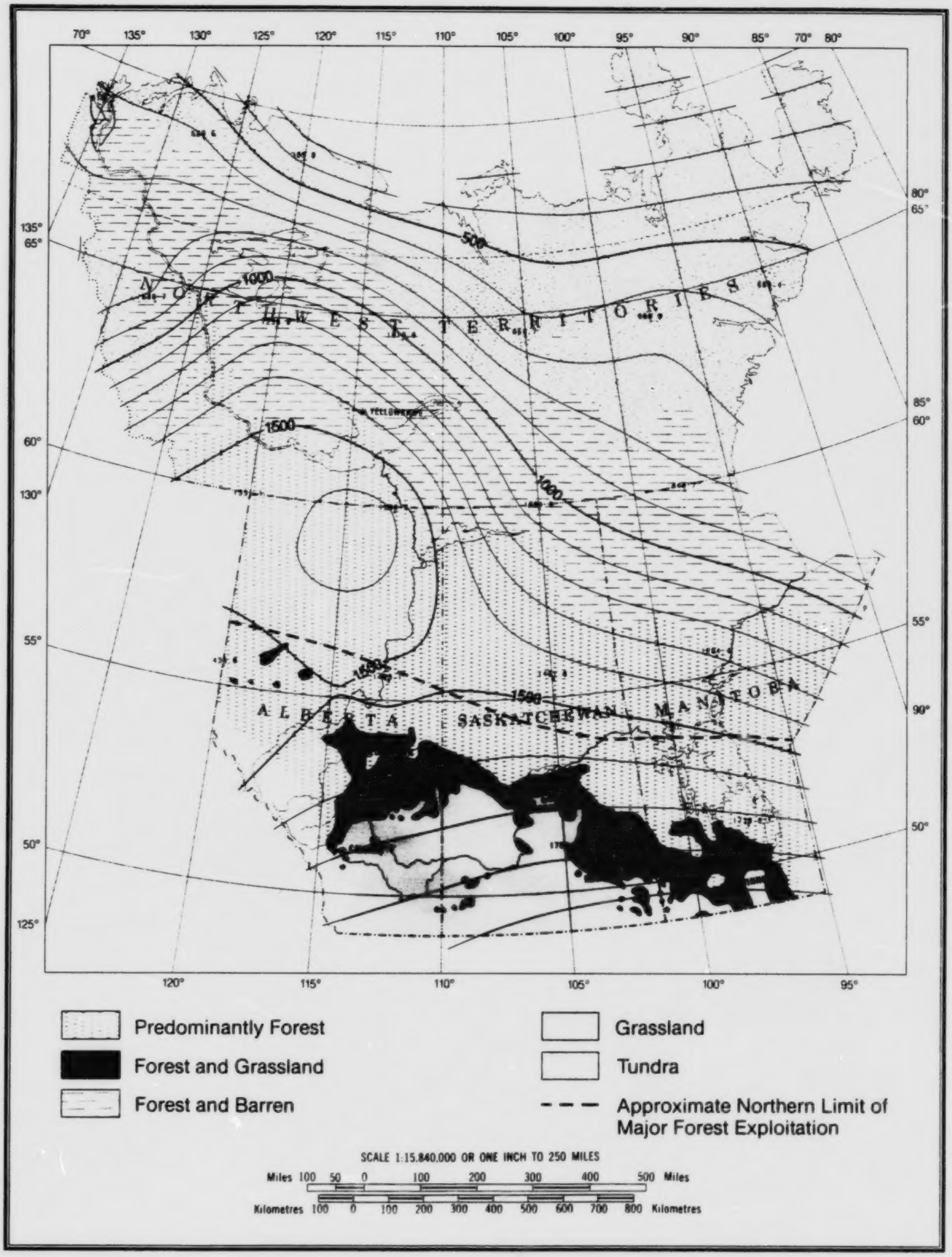
55°
90°
50°
120°
115°
110°
105°
100°
95°
500
1000
1500
1000
1500
1500
NORTHWEST TERRITORIES
ALBERTA
SASKATCHEWAN
MANITOBA
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure 4.1 Mean Annual Growing Degree-Days (Above 5°C) for the GISS-Based Climatic Change Scenarios.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NORTHWEST TERRITORIES
YELLOWKNIFE
ALBERTA
SASKATCHEWAN
MANITOBA
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure 4.2 Mean Annual Growing Degree-Days (Above 5°C) for the GFDL-Based Climatic Change Scenarios.

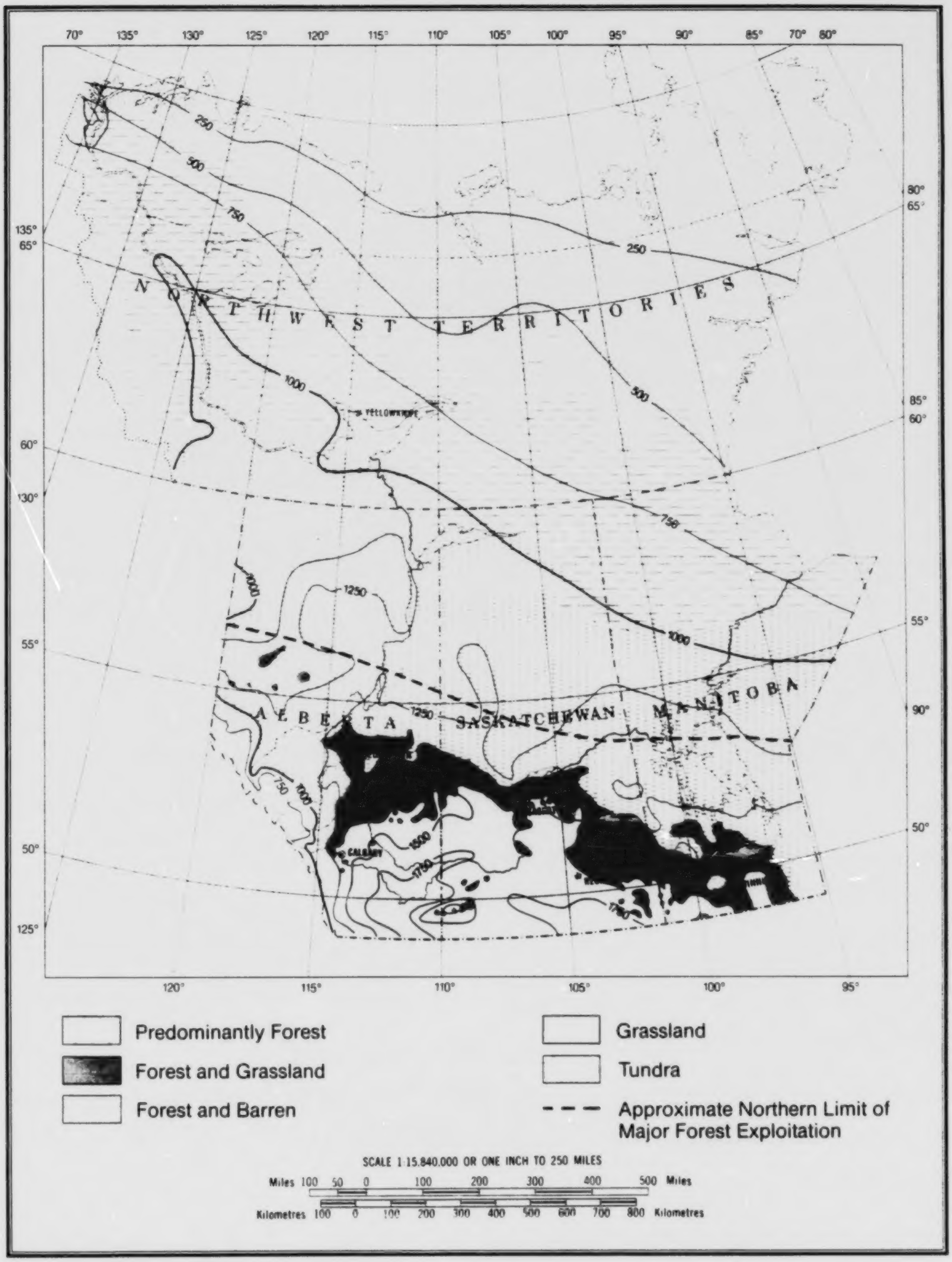
NORTHWEST TERRITORIES
ALBERTA
SASKATCHEWAN
MANITOBA
YELLOWKNIFE
CALGARY
250
500
750
1000
1250
1500
1750
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure 4.3 Mean Annual Growing Degree-Days (Above $5^{o}C$) for the 1951-1980 Period (HIST).

Source: For growing degree-day isolines is Environment Canada (1987).

location will also undergo considerable change. The shift of this limit would be about 400 to 980 km as suggested by the GISS-based scenarios and about 200 to 900 km for the GFDL-based scenarios.

The implications of these potential shifts of the climatic resources for forests and eventually of the forest regions are quite serious and planning for adjustments would be advisable.

The results for the precipitation index suggests that the mean moisture resources for forestry would increase by 3 to 22% for the representative GISS1 gridpoints and by 6 to 17% for all but the most northerly of the GFDL1 gridpoints, that showed a decrease of 6% below normal. So the possibility of increased moisture stress that is associated with higher temperatures would generally be offset by the increases of precipitation that are also estimated by the GISS1 and GFDL scenarios.

When the normal precipitation amounts and the temperature increments of the GCMs are used as in GISS2 and GFDL2, both scenarios exhibit decreases for precipitation effectiveness for all the selected gridpoints. This implies that if the precipitation does not increase along with the temperature increases, that the moisture resources would deteriorate. Some species could be adversely affected, but others that are limited by excessive moisture may exhibit improved growth.

Precipitation effectiveness should be calculated for all the available gridpoint data sets and mapped in order to study the remainder of the study area. The meaning of these changes for the forest should also be assessed.

The effects of a change in climate on potential biomass productivity is also examined especially by means of a method that includes thermal, moisture and solar factors and is suitable for a range of species. If the results are applicable to a range of species then it would be more useful in the process of selecting appropriate species for growing in an area. The model used herein for preliminary assessments of changes in biomass potential is the climatic index of agricultural potential (Turc and Lecerf 1972), CA. Again, the twelve monthly products of the heliothermic and moisture factors are used to compute CA. The mean annual values of the heliothermic and moisture factors are also provided in Table 4.1. Again, it should be noted that CA has not been tested against actual productivity data for the study area and this should be done in future studies.

Climatic warming with increased temperature and precipitation (GISS1 and GFDL1 scenarios) resulted in a considerable increase of potential biomass, as indicated by CA, for all but the most southerly of the gridpoints evaluated. The ranges of CA were 1 to 58% above normal for the GISS1 gridpoints and 22 to 118% above normal for the GFDL1 scenario. The two scenarios appear to have contrasting spatial patterns, with the GISS1 values increasing from south to north and the GFDL1 values decreasing from south to north.

Climatic warming without the increased precipitation, that is, with normal precipitation amounts (GISS2 and GFDL2) were also considered. The GFDL2 scenario resulted in higher than normal CA values, ranging from 5 to 44% above normal. The GISS2 scenario showed an increase in CA values above normal only for the more northerly locations with a range from 12% in the south to 27% in the north. The more southerly locations exhibited decreases of 2 to 12%.

There are some intriguing patterns starting to emerge that cannot be properly evaluated using only a few gridpoints. If CA corresponds well with actual productivity data, CA should be calculated and mapped for all of the available gridpoints to more rigorously examine this effect. The change in the characteristics of the climate throughout the year can and should also be examined using such an approach. Annual values alone are not sufficient to examine the impacts of changes within the growing season, for instance.

4.3 Preliminary Comparisons of Models with Productivity and Zonation Information

As explained in Section 3.4, a simple model relating forest productivity to climate was developed. Multiple linear regression analysis of mean annual increment (MAI) on potential evapotranspiration (PE), which depends mainly on temperature, and an index of moisture (IM), for 21 forest sections in the study area, produced the relationship shown in Section 3.4. Another independent variable expressing geological variability among the forest sections was also tested, but it increased R^2 only to 0.78.

Even with this limited data set, there is significant positive relationship of forest growth rate to both growing season temperatures and moisture availability. This shows the desirability of carrying out a similar analysis using the much larger amount of climatic data available. It also clearly indicates that moisture effects, and not just temperature effects, must be considered in projecting the productivity of forests in this subhumid western part of the boreal forest.

The second model deals with the climatic determination of the zonation of the boreal forest. This zonation model simply assigns a station to a vegetation zone based on its growing degree-days and precipitation values. As explained in Section 3.4, the tundra/subarctic, subarctic/boreal, and boreal/boreal-temperate boundaries are defined by values of degree-days above 5°C, while the boundaries with parkland and grassland are defined by regression lines relating degree-days to annual precipitation (Figure 4.4).

Random checks show that the model usually makes correct assignments, although errors are sometimes made for stations close to zonal boundaries. The model was applied to four gridpoints from the GFDL1 scenario, first using the normals (representing present climate), then using the simulated growing degree-days and precipitation for doubling of atmospheric CO_2. The results indicate that present vegetation zones were assigned correctly for the present climate. Under the simulated warmer climate, the subarctic gridpoint and one boreal gridpoint were converted to aspen parkland, while the other boreal gridpoint became boreal-temperate (Table 4.2).

These results demonstrate the importance of modelling zonation in relation to climate, as the changes in zonation resulting from climatic change could be dramatic. They also underscore the need to consider both moisture and temperature effects in this region. Instead of the simple northward shift of the boreal zone predicted by Kauppi and Posch (1984) based on temperature alone, this model suggests the extension of aspen parkland into the western part of the zone and boreal-temperate forest into the eastern part of the zone. Refinement of this model based on the much greater amount of available climatic data is clearly justified.

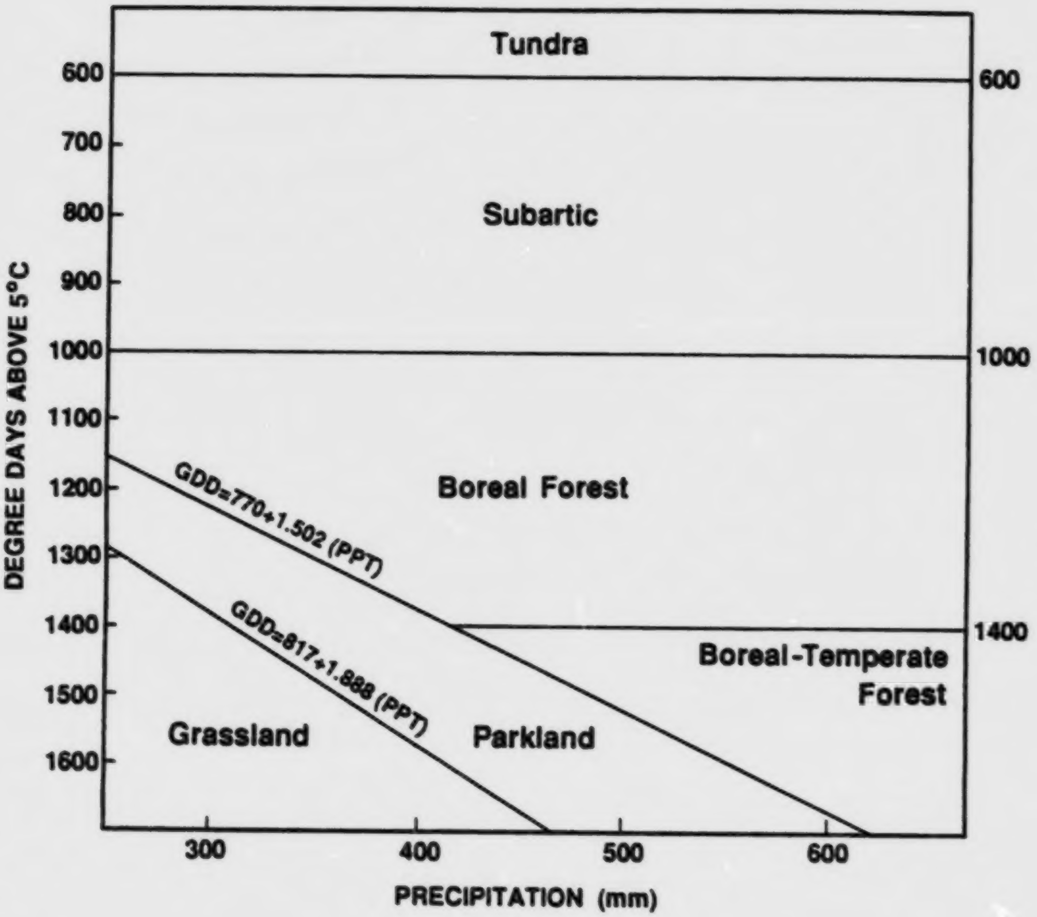

Figure 4.4 The Boreal Zonation Model - Criteria for Assigning Stations to Vegetation Zones.

Table 4.3. Change in Vegetation Zonation as Implied by the GFDL1 Climatic Change Scenario (ie. with precipitation increases).

Gridpoint Location (latitude, longitude)	Present Zonation	GFDL1 Zonation
64.4° N, 120° W	subarctic	aspen parkland
59.9° N, 120° W	boreal	aspen parkland
55.5° N, 105° W	boreal	boreal-temperate
51.1° N, 112.5° W	grassland	grassland

4.4 Effects of Climatic Change on Forest Fires and Insects and Diseases

Any forecast of changes in forest fire frequency and behavior is extremely speculative because the frequency of weather patterns conducive to fire is uncertain. However, given that temperature is generally expected to increase, forest fire activity will probably increase. Management response is expected to be strongly related to changes in the frequency of extreme fire seasons. Given the unpredictable nature of fire and the uncertainty of future climate, such a response is probably appropriate and inevitable. Therefore, it would be appropriate to continue to explore these relationships.

The relationships of the current insect and disease problems to climate are well defined only for selected pests such as the mountain pine beetle. Considering that insect and disease activity will probably increase with the expected changes in climate, much work is required.

4.5 Climatic Change and Forest Management

The importance of matching the time response of various systems to the time scale of climatic change was mentioned previously. In public forest management in Canada, current annual allowable cuts are based on projections of volume over a time span of at least one rotation. Planning horizons of two rotations or more are frequently used (Alberta Forest Service 1985). Planning horizons of one to two rotations mean that climatic variability and climatic change are important to current timber management decisions because they will influence future growth. It is the projected growth which is the basis for current harvest rates.

From the literature review on climate and productivity, it is apparent that growth can be influenced by climate in two distinct manners:

1) Within a fixed genetic framework, trees and stands are able to respond to changes in climate (phenotypic plasticity).

2) Trees and stands are able to genetically adapt to changes in climate to more fully utilize a favorable growth environment.

The time span required in the adaptation process is well beyond the response time of the timber management system. That is, current management decisions will be unaffected by any growth enhancement occurring through adaptation of a genotype due to climatic change. However, phenotypic plasticity of existing genetic stock may be important. Two possible forest states may occur in the future which directly affect the importance of determining the sensitivity of existing genetic stock to climate.

1) If existing genetic stock continues to regenerate either naturally or artificially, then knowledge of phenotypic plasticity is very important. The sensitivity of stands to climate will affect the growth of regenerated timber as well as standing timber.

2) If superior genetic stock is introduced to take immediate advantage of a changed climate, then the importance of determining the sensitivity of existing growing stock to climate will be diminished. However, the sensitivity of existing stands will still be meaningful because it will influence the growth rates of standing timber but its importance will decrease as standing timber is harvested and replaced by introduced growing stock.

The magnitude of climatic variability relative to predicted climatic change has important implications for growth. As Mitchell (1961) and Jones et al. (1982) and others have indicated, substantial variation in climate occurs due to factors such as volcanic activity. These unpredictable variations are probably more relevant in the short-term to forest growth than is climatic change. These short-term variations in climate may be particularly important in the interpretation of real growth data collected over short-time spans. Knowledge of the sensitivity of forest stands to climatic variables is of concern even without climatic change.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Scope of the Study

This study has concentrated on the literature that is relevant to climatic change impacts on the boreal forest and forestry and on the methodology available to assess these possible impacts. Much literature was reviewed and appraised in view of climatic change impact assessment. Many questions and areas of little knowledge were suggested by this literature review and consolidated in this report.

The literature that is directly related to the study is sparse and thus much of the preliminary quantitative and even qualitative climatic impact assessment has not been previously undertaken. Many assumptions had to be made and thus several limitations are imposed upon this work. Many are not too different from the range of normal assumptions applied in scientific work, but others are fairly new because of the recent emergence of the field of climatic change impact assessment. Newer assumptions include those surrounding the development of the climatic change scenarios. These limitations are stated within the work in the appropriate positions. The preliminary new work accomplished for this study include:

1) The development of a dynamic economic model for measuring the potential benefits of climatic change.

2) The illustration and description of the time and space characteristics of climatic change scenarios for the study area.

3) An index of potential biomass productivity and its component factors were used to explore the impacts of the climatic change scenarios on the boreal forest of the study area.

4) A multiple linear regression relating forest productivity to

climate was developed and tested.

5) A climatic zonation model for the boreal forest was designed and tested. Results of the impacts of one of the climatic change scenarios were calculated and discussed.

6) A method assessment framework was created and applied to various impact models.

7) A system diagram to illustrate and explore the climatic change-forest-economics-policy interactions was designed. Interdisciplinary work was promoted and the authors cooperated to integrate the study.

Then a series of recommendations were formulated based on the literature review as well as the methodology and initial climatic impact assessments. The recommendations are organized by section and often by short- and long-term basis. They are presented in the following sections.

5.2 Climatic Change/Variability Scenarios

There are several means of improving the climatic change scenarios and they include:

1) More information is required from the GCM experiments. One of the first requirements is better temporal and spatial resolution. We need to know more about the extreme climatic events and the effects on the frontal positions, and we need climatic change information for more closely space gridpoints. We also need information about the statistical distribution of climatic parameters, such as the variance, rather than just the mean.

Other additional information required from GCMs includes the position of fronts and storm tracks, evaporation, soil moisture and wind speed and direction. The frequency of extreme weather events is important as a control of fires and mechanical damage to trees. The additional information gleaned from the GCM experiments to simulate the observed climate should then be tested against observational data for the study area.

Work should continue on improving the GCMs as they are one of the best projections of future climate. The direction and rate of change of precipitation, for example, seems to be especially questionable and this should be examined more closely. This is a project to be tackled by the GCM modellers.

2) More hybrid climatic change scenarios should be utilized and developed in the interim, while GCMs are being improved and while more data is being provided from them. In the shorter-term, impact modellers can use hybrid scenarios to provide estimates of the effect of extreme events and of the effect of a sequence of years, as well as to improve spatial and temporal resolution of climatic scenarios.

3) At least one more set of GCM results should be used in the next impact study as a basis upon which to build climatic change scenarios. Only two GCMs were used in this report and the use of more would foster a better exploration of the sensitivity of the forest to climatic variables.

4) Analogue areas should be sought that have present climates comparable to the study area scenario climates. Then the relationship between the climate of the analogue area and forestry can be examined to determine the sensitivity of this relationship in the climate of interest.

5.3 Tree Physiology, Forest Ecology, Direct Effect of CO_2, Tree Growth and Forest Zonation

Further study of the direct and indirect effects of increasing levels of CO_2 on boreal forests is of long-term ecological interest. An important reason for pursuing the areas of study mentioned above is the economic reason as explained in Section 1.2. Forest management planning is commonly carried out for periods of seven to ten years. The CO_2 question has tremendous implications for long-term timber supplies and manufacturing, and it adds uncertainty concerning the success of reforestation and stand tending activities. Recommendations in Sections 5.4 and 5.7 deal with these implications more specifically, but fundamental species and ecosystem information is essential as a basis for evaluation of the importance of environmental change to forest management.

Recommendations relating to tree physiology, CO_2 fertilization, forest ecology, and forest zonation follow:

1) Basic, controlled environment studies need to be carried out on all of the commercially important tree species. Little is known about the basic physiological and growth responses of boreal tree species to critical limiting factors of the environment such as CO_2, air and soil temperature, soil moisture, relative humidity, and nutrients. This is true regardless of increasing CO_2, and it is true of the principal, economically important tree species as well as the less important species.

2) Modelling efforts are needed to simulate physiology and growth beyond the seedling stage and to identify critical areas where research should be carried out. Virtually no information on CO_2 effects or of basic environmental limiting factors on physiological processes in trees

beyond the seedling stage is available. Long-term information on such growth responses as diameter and height growth is more prevalent than physiological data but is limited for some species. In addition, growth data on such matters as change in leaf area over time are not available for even the economically important species. Modelling to develop estimates regarding the long-term effects of CO_2 increase on trees is recommended. Effects on tree diameter, leaf area, root to shoot ratios and nutrient requirements, etc. would be useful to assess. Thinning studies, fertilizer data, etc. could be used to provide inputs for this purpose. Modelling is suggested as the method, using whatever information is available, because the results of short-term experiments are questionable and we cannot wait for long-term results.

3) Studies of basic responses of species with current or potential competitive effects on economically important tree species should be carried out. Direct CO_2 effects on boreal species other than trees are virtually absent. In most cases, common climatic effects on growth and physiology of these species are not available either. The most important species to study are grasses and shrubs which increase in population size following harvest or fire and which impact on successful stand regeneration and establishment.

4) A modelling effort to bring together available information on nutrient cycling, hydrology, and natural succession should be initiated. Without this effort, attempts to evaluate ecosystem boundary changes and changes in ecosystem function are bound to be too simplistic, and perhaps totally misleading. Questions such as the effects of atmospheric warming on decomposition rates and the relative responses of hardwood vs. coniferous forests need to be addressed both through

modelling and experimentation. Data on ecosystem processes in boreal forests are few and scattered.

5) A number of problems with modelling need to be addressed. Modelling evapotranspiration is difficult as is the assessment of the implications and magnitude of possible effects of improved water use efficiency. The implications of genetic variability among populations and acclimation potential within populations must be considered but will be difficult to model until more information is available on the magnitude of these two factors.

6) Better empirical models of climatic determinants of vegetation zonation should be developed. Climatic data for a large number of locations in each zone should be used in conjunction with discriminant analysis to obtain functions to separate the zones. Then this zonation model(s) can be used to map the changes in vegetation zones under climatic change. This work can be done in the shorter-term.

7) In the long-term, a combined empirical/mechanistic model(s) appropriate to forest growth in this region should be developed and existing models should be used as the basis for this development whenever possible.

5.4 Forest Productivity

1) There is a need to relate short-term historic climate to measures of stand (and tree) productivity. A cost- and time-effective method to achieve this would be to locate forest stands near climatic stations that have records for periods of at least 10 to 15 years. Shorter records would probably lack the variability in annual climate to establish meaningful relationships. Detailed growth layer analysis of

trees would provide the records of productivity which could be matched to the climatic variables. The variability in climate year-to-year is likely to be great enough to establish useful relationships and it will avoid uncertainties relating to previous stand conditions and climate.

2) The effect of climatic change on wood quality and density needs to be determined, as the climatic factors affect the rate of growth and thus the resulting quality of timber.

3) The dendroclimatological approach may be helpful to explore some of these trends in wood density as suitable warmer periods may provide appropriate data and some answers to our questions. The approach should be assessed more carefully in view of some of the warming trends that have occurred during the past and the warming trends that may occur in the future.

4) The forests and forestry in areas which have present climates similar to climatic change scenario climates need to be studied. This could give some indication of the probable species and management that would be suitable for the study area in a changed climate.

5) Simple regression-type models relating forest productivity data to climatic variables should be developed. We need to search for ways to remove the influence of geology, soils, stand structure and competition in order to improve the climate/productivity relationship.

6) Other existing forest production models that can use climatic data should be developed and tested for the purpose of climatic impact assessment. For instance, Turc and Lecerf's climatic index of potential biomass productivity should be calculated for the rest of the gridpoints in the study area for both historical and climatic change scenarios to estimate potential changes. The relationship of this index to

productivity data for the study area should be tested.

The FAO general biomass production model (de Wit 1965) also appears promising for the assessment of climatic change impacts on forest production. The estimates from this model generally correspond well with potential forest productivity (CLI) in drier regions (Clark, no date). This model should be calculated for various climatic change scenarios and results assessed.

7) Existing forestry yield tables for specific sites may need to be adjusted based on the results from the climate/productivity models. This will provide the yield information needed for the economic models in further studies.

5.5 Forest Fires

1) Climatic change would affect the intensity and frequency of forest fires. The frequency of extreme weather events largely controls fire weather severity. The change in frequencies due to climatic change need to be determined and related to forest fire potential.

2) The increase in temperature and growing season length beyond the present limits could be devastating in many cases and will put strain on the efforts needed for effective fire fighting and fire prevention. These effects need to be investigated properly by using the Canadian Forest Fire Danger Rating System.

5.6 Forest Insects and Diseases

The warming of climate, increase in growing season length, and the accompanying change in precipitation patterns and amounts will have impact on pathogens. The insect and disease occurrences and forest infestations need to be understood clearly to devise preventive measures. The health and well-being of our forests depend on the timely action taken on these priority matters.

5.7 Forest Hydrology and Logging Operations

1) The change in snow accumulation and winter temperatures and length would imply changes that will need to made in the choice of logging systems and timber harvesting practices for the existing forests. So the changes in these parameters and their effects on logging systems and timber harvesting practices need to be quantitatively assessed and modelled, if possible.

2) Climatic change will also have an impact on forest and range hydrology. The frequency and intensity of droughts in a warmer climate should be explored as they affect regeneration and establishment of seedlings to replace the areas cut or burned, and as they affect tree growth, survival and zonation.

3) More information about soil moisture capacities and soil nutrient status for the study area is required as this information is essential to more accurately model the response of the forest, especially with a shift to warmer climates.

5.8 Economics

Economists consider climate to be a resource similar to other resources used in the production of goods and services, albeit with some rather unique characteristics. And, in evaluating the economic impacts of changes in climate, it has to be treated similarly to other natural resource.

The economics of climatic change was investigated in this study by reviewing methodological issues and examining studies which have considered the economic effects of climatic changes. These studies have looked primarily at agriculture. Unfortunately, there was little in the agricultural studies useful for the current investigation, particularly if the major change in forest value occurs through changes in the nonmarket functions. There are some studies in the forestry literature which provided some guidance for evaluating changes in commercial timber values, and there are others which examine preservation value, although not existence value. In addition, work by economists on welfare measurement and the economics of climatic change, sparse as the latter is, provide some guidance for the recommendations provided below.

It is important that one is clear regarding the economic concept which is to be measured. There is frequently confusion regarding the difference between economic benefits and economic impacts (or indirect effects). Economists consider only the changes in the economic surpluses of economic agents, namely, producer rent and consumer welfare (e.g. consumer surplus), to be valid measures of the economic benefits or costs brought about by changes in climate.

The following recommendations are made if further research concerning the economics of climatic change impacts on the western boreal forest region, or for that matter other Canadian forest regions, is to be pursued.

1) A major concern is with changes in timber value due to changes in climate, therefore two recommendations follow.

(a) The correct measure of the economic benefit from climatic change is given by the difference between the discounted stream of benefits obtained from an appropriately specified dynamic model without the change in climate and the discounted stream of benefits under the new climatic conditions. That is, it is the difference in the discounted stream of benefits for two optimal time paths for exploiting the forest, one without the change in climate and the other with the change in place. It is possible, of course, that the latter permits climate to change gradually.

(b) The benefit function employed in the dynamic model should be specified according to that specified in Section 3.5.2. The benefit function must take into account international trade and should consider the possibility of changes in the forest supply of other regions in the world and in Canada as these regions will also be affected by changes in climate. This will require the use of an international, econometric trade model simply to identify the elasticities of supply and demand, and, if supply shifts in other regions are to be permitted, to identify how the supply functions in the other regions will be affected.

In order to achieve these goals, however, it may be necessary to first construct an applied general equilibrium (GE) model which includes consumers and timber producers in several regions. Shaven and Walley (1984) provide an example of how this can be done in a trade setting. The applied GE model can be used to determine not only the aggregate change in economic well-being (welfare), but can also be used to identify who gains and who loses and by what amount.

2) Future research must not only consider changes in commercial timber production, but must attempt to value the changes in nonmarket amenities which occur when climatic changes occur. There are two functions of the western boreal forest which must be taken into account

in attempting to identify the economic benefits or costs of changes in climate. In addition to commercial timber production, it is necessary to consider the net economic benefits associated with recreational, scenic, and other amenities of the boreal forest (e.g. global weather regulation, pollution sink and watershed functions). As these amenities are affected by changes in climate, they cannot be ignored. Future research must attempt to value the changes in nonmarket amenities which occur when permanent or long-term climatic changes occur.

3) The Leslie equation approach offers an excellent opportunity to integrate risk and uncertainty caused by forest fires and disease into the dynamic economic model (Section 3.5.1.2). The Leslie equation approach should be adopted to handle the physical requirements of the economic model.

4) Future research should be conducted in conjunction with FEPA (Forest Economics and Policy Analysis Project at the University of British Columbia) as they are currently involved in both econometric modelling and ecosystem modelling using the Leslie equation approach. Dr. Ilan Vertinsky, Director of FEPA, indicates that FEPA would be willing to work closely with scientists interested in joint research and this is an approach which should be considered.[1]

5) Finally, it may be that the preservation, pollution-abatement and water storage values of the western boreal forest are greater than

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[1] FEPA consists of a number of physical scientists located at FEPA offices at the University of British Columbia and independent researchers who coordinate their research through, and obtain minor amounts of funding from, FEPA. However, FEPA is looking to conduct more economics research. Therefore, the principal investigator for the economics section of this interdisciplinary study is currently in contact with Dr. Vertinsky, and will be working at FEPA during his sabbatical year, 1988-89.

all other values of this forest as noted in Section 3.5.3. It is also these values that may be affected most by changes in climate. However, no theoretical or empirical work to determine such values for the northern forests, or for any other resource has been done. Therefore, it is imperative that research in this direction be undertaken.

This will require climatologists and other physical scientists to identify the role which the northern forests play in the world ecosystem. That is, it will be necessary to identify how changes in forest vegetation caused by changes in climate affect water storage, the capacity of the forest as a waste receptor, and so on. The role of the economist will be to identify appropriate measures of these forest demands and provide empirical estimates of the benefits or costs associated with a change in the nonmarket functions of the forest. This is an important research task.

5.9 Policy Implications

1) Climatic change will have tremendous implications because of shifts in agricultural and forestry zones. There will also be definite changes in productivity, species, forest fires, drought occurrences, etc. These have to be addressed as matters of great concern to inhabitants of these provinces, in particular, and to Canada as a whole. Forestry and agriculture policy formulation should be planned in time for solving many of the problems arising out of the future climatic change. Such planning and policy formulation is essential for taking maximum advantage of beneficial impacts and for minimizing all deleterious impacts.

2) A case study should be undertaken to determine the possible

impacts of climatic change on the forest industry. A shift in the present boundaries of the Forest Management Area of a pulp mill, for example, could have serious consequences and management implications for the successful operation of a company or industry. These problems have to be dealt with seriously and realistically to suggest possible solutions. A case study will also be needed for assessing the effects of climatic change on the many nonmarket benefits and amenities dependent on forests.

5.10 Systems Analysis Approach and Conclusions

The dialogue among disciplines must be continued in order to develop the model linkages of the system into a coherent whole, and to best determine what information is needed from one another. The systems analysis approach has many merits for use in an interdisciplinary study such as this one. Since the authors have just begun to understand each others professional language, we made only a preliminary exploration of the linkages among the different impact models (Figure 3.5). Now that we have explored the range of methods and made some selections and some trial impact assessments, we are at a stage where we must test and develop the impact models. Then climatic changes/variations can be translated into a much improved and more complete range of forest and economic impacts.

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APPENDIX A

COMMON AND SCIENTIFIC NAMES OF TREE SPECIES

Austrian pine	*Pinus nigra* Arnold.
balsam fir	*Abies balsamea* (L.) Mill.
balsam or black poplar	*Populus balsamifera* L.
bigtooth aspen	*Populus grandidentata* Michx.
black spruce	*Picea mariana* (Mill.) B.S.P.
bristlecone pine	*Pinus aristata* Engelm.
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
eastern larch or tamarack	*Larix laricina* (Du Roi) K. Koch.
Engelmann spruce	*Picea engelmannii* Parry.
jack pine	*Pinus banksiana* Lamb.
labrador tea	*Ledum groenlandicum* Oeder.
lodgepole pine	*Pinus contorta* Dougl. var. latifolia Engelm.
marsh reed grass	*Calamagrostis canadensis*
Norway spruce	*Picea abies* (L.) Karst.
paper or white birch	*Betula papyrifera* Marsh.
radiata pine	*Pinus radiata* D. Don.
Scots pine	*Pinus sylvestris* L.
sitka spruce	*Picea sitchensis* (Bong.) Carr.
soybean	*Glycine max* L. Merrill.
sweetgum	*Liquidambar styraciflua* L.
tamarack (eastern larch)	*Larix laricina* (Du Roi) K. Koch.
trembling aspen	*Populus tremuloides* Michx.
tulip-tree	*Liriodendron tulipifera* L.
western white pine	*Pinus monticola* Dougl.
white (paper) birch	*Betula papyrifera* Marsh.
white oak	*Quercus alba* L.
white spruce	*Picea glauca* (Moench.) Voss.
yellow poplar (tulip poplar)	*Liriodendron tulipifera* L.

APPENDIX B

NOTES ON EVALUATION OF FOREST GROWTH MODELS

The following points were considered in evaluating models. In the comments on individual models which follow, only those points relevant to evaluating each particular model are mentioned. The assessment of each model is based on suitability for the purposes of the present project.

1. Input data - should mainly consist of simple climatological data at a reasonable time interval (e.g. monthly or yearly) which is available or can be estimated for stations in the study area. Biologically meaningful data preferred (e.g. growing-season temperatures rather than mean annual temperature, moisture balance rather than simple precipitation).

2. Parameters - should either already be estimated using boreal forest data, or should be newly estimable.

3. Output - in order of preference:

1) forest volume increment curves over the length of the rotation, directly usable in forest economics models.

2) mean annual increment (MAI) of wood volume based on rotation age, or net primary productivity (NPP) of biomass (which can be converted to wood volume), which can then be used to adjust volume increment curves.

3) values which can be correlated with MAI or NPP, such as annual net photosynthesis, or various synthetic indices or productivity.

4. Sound theory and structure.

5. Verified or verifiable.

6. Accessible and documented.

CLASSIFICATION OF MODELS:

1 HIGHLY EMPIRICAL MODELS

1.1 Simple Regressions:

- relate some simple measure of growth, such as MAI or NPP, to simple climatological variables. These models have appropriate input and output and have the advantage of simplicity. All would require verification tests against data for the study area, and possibly new estimation of parameters using such data.

1.1.1 Lieth's Miami Model (Lieth 1975, 1976, 1978; Pittock and Nix 1986):

- regressions of NPP against mean annual temperature and against annual precipitation for stations around world. Model predicts NPP based on lesser of predictions from temperature and from precipitation.
- assessment: too general; wide dispersion of points about regressions; inappropriate climate data for biological processes. Availability: published.

1.1.2 Downing and Weber (1976):

- regression of net aboveground biomass increment on climate data (mean annual temperature and annual precipitation) and stand data (biomass, age, etc.) for forests around world.
- assessment: better prediction than Lieth's, but still uses inappropriate climate data. Availability: published.

1.1.3 Dendroclimatological Methods (Fritts 1976):

- regression of tree-ring widths or densities against annual weather variation.
- assessment: Unsuitable: requires large tree ring data base; existing literature has not produced clear climate/tree ring relationships for main boreal forest. Availability: published.

1.1.4 Kauppi and Posch (1985):

- regression of annual tree growth rate in Finland on effective temperature sum.
- assessment: gives good fit and uses appropriate climate data; however moisture variables should also be used for western Canadian situation. Availability: published.

1.2 Complex Bioclimatic Indices:

- multiplicative functions of terms related to radiation, temperature, and moisture availability, which are correlated with productivity. These indices should be verified against productivity data from the study area to determine their applicability.

1.2.1 Paterson's CVP Index (Lemieux 1961):

- multiplies a temperature term, annual precipitation, a season-length term, and a radiation term; correlated with forest productivity in Sweden.
- assessment: appears to be theoretically questionable; Lemieux found that simple multiplication by precipitation gave excessive values for productivity of cool, wet stations. Availability: published.

1.2.2 Turc and Lecerf's Climatic Index of Agricultural Potential:

- calculates a dryness factor based on monthly soil water balance calculations; calculates a heliothermic factor based on monthly radiation and temperature; dryness factor and heliothermic factor are multiplied to give climatic index.
- assessment: appears to be preferable theoretically to Paterson's index; dryness factor and heliothermic factor can be considered separately. Availability: published.

2 INTERMEDIATE MODELS

These models are intermediate between the highly empirical models above and the highly mechanistic models below. Validation of these models is generally very limited, except as noted, and sensitivity analyses are generally absent or not reported.

2.1 Webb et al. 1983:

- simple model of net primary productivity of forests based on radiation, mean annual temperature, foliage biomass, and total aboveground biomass; parameters estimated against 15 US/IBP forest sites.

- assessment: approach is simple and data requirements are realistic; but does not include moisture effects; temperature measure is crude; parameters would have to be estimated using boreal data. Availability: published.

2.2 JABOWA, FORET, FORENA, etc. (Botkin et al. 1972; Solomon et al. 1981; Solomon 1986):

- a large family of models with similar structure; oriented to prediction of long-term succession; operates at level of individual trees grouped within small plots; simulates birth of new trees, growth of trees, and mortality; growth routine consists of a function for optimum growth (uses leaf area and biomass as input, with parameters adjusted to match function to literature values for largest trees of species), multiplied by limiting factors ranging from 0 to 1; limiting factors consist of light (based on position of tree in canopy), temperature (growing degree-days at site compared to assumed response function for species based on temperature sum at its northern and southern limit), and moisture (based on soil water balance calculations); annual increments of forest volume can be extracted from simulations.

- assessment: model has already been applied to the boreal forest by Solomon (1986); parameters are easily estimated from standard information for tree species; input data are standard weather data; but growth routine is simplistic, based on assumptions rather than real growth information; temperature effect is modelled inappropriately, based on assumption that growth rate of tree species approaches zero at its southern range limit. Validation based on approximate prediction of present forest types for present climate, but in fact gives wrong species dominant in boreal forest. Availability: FORET listing published in Shugart (1984).

2.3 Index of Photosynthesis (Emmingham and Waring 1977):

- relative index of net photosynthesis in Douglas-fir; daily calculation based on response of photosynthesis to average temperature and radiation, multiplied by stomatal conductance; moisture stress, cold soil, and night frost are modelled as reducing stomatal conductance. Requires as input daily day and night temperatures, shortwave radiation, xylem water potential and soil temperature. Parameters estimated based on physiological research on Douglas-fir, but has been used as a relative index for a wide variety of ecosystems by Emmingham (1982). Well correlated to site index of Douglas-fir stands.

- assessment: data requirements are excessive in model's present form; temperature and radiation data probably could be estimated from weather records, but xylem water potential not available; some other method would have to be found to estimate moisture effects on stomatal conductance; parameters based on Douglas-fir inappropriate for study area; some could be modified using physiological information available for boreal species. Availability: formulae in the publication.

2.4 SUCSIM (Reed 1980):

- succession model similar in intent to JABOWA, but models growth of cohorts of trees; growth routine simulates optimum growth (parameters estimated by matching to Douglas-fir site index curves) modified by multiplicative limiting factors: light (based on position in canopy), temperature (based on information on growth response of Douglas-fir seedlings to daily air and soil temperatures) and moisture stress (based on a model of transpiration which requires daily data on Xylem water potential and water vapour concentration gradient); annual increment of forest volume can be extracted from the model.

- data requirements are excessive as model now stands; temperature data could be estimated from weather records, but water potential and vapour concentration gradients are not available, so simpler modelling of effect of moisture stress would have to be substituted; parameters based on Douglas-fir are inappropriate for study area, so parameters would have to be reestimated. Availability?

2.5 FORCYTE (Kimmins 1986):

- based on forest yield tables, the empirical measure of productivity, but certain ecosystem processes are simulated to modify yields, to allow prediction of effects of management. At present, changes in light regime and changes in nutrient supply from decomposition are the main processes simulated.
- assessment: this model is site-specific, so does not model climate variation; temperature and moisture effects not presently modelled (but will be included in future versions); therefore not suitable for our purposes. Availability: listing available from author.

2.6 Northern Ecosystems Carbon Simulator (Miller et al. 1983):

- a complex ecosystem model of the carbon flux in the entire boreal and arctic zones of the world, broken down by vegetation zone; includes model of growth in biomass, limited by both carbohydrate supply (from photosynthesis and respiration) and nutrient supply (from decomposition), both of which are affected by temperature; photosynthesis is also affected by variable carbon dioxide concentration; only climate data required are mean annual temperature and annual amplitude of temperature, from which monthly temperatures are simulated; requires large number of parameters, many of them not measured.
- assessment: approach is interesting, especially in that effects of rising temperature on soil processes are modelled; but moisture stress not modelled; already applied to boreal forest, but many of the parameters roughly estimated, some of them in error; their runs predict higher present productivity in mid-boreal forest than southern boreal forest, contrary to known patterns; probably too many parameters to estimate to give better results. Availability: listing available from authors.

3 MECHANISTIC MODELS

Models which attempt to model physiological processes mechanistically. These are the most sophisticated models for the processes involved, but their high data requirements and fine time scale make them inappropriate for the purposes of this study.

3.1 Model of Photosynthesis (Reed et al. 1976):

- hourly (or more frequent) calculations of photosynthesis, requiring as input data irradiance, temperature, ambient carbon dioxide concentration, and stomatal conductance. Many parameters estimated, specific to the species used.
- assessment: inappropriate.

Similar models for Scots pine appear in Persson (1980).

APPENDIX C

CHANGED CLIMATES THROUGH TIME AND SPACE

(For doubled atmospheric carbon dioxide)

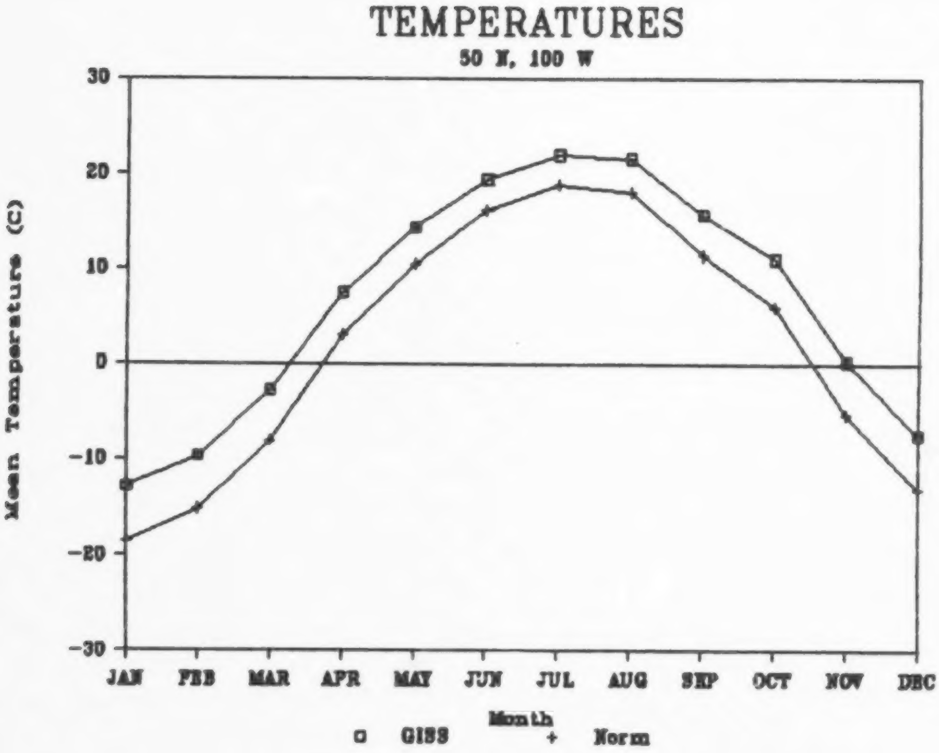


Figure C.1a Comparison of 1951-80 Normal (HIST) Monthly Temperatures with GISS Climatic Change Scenario Monthly Mean Temperatures for a Specified Gridpoint.

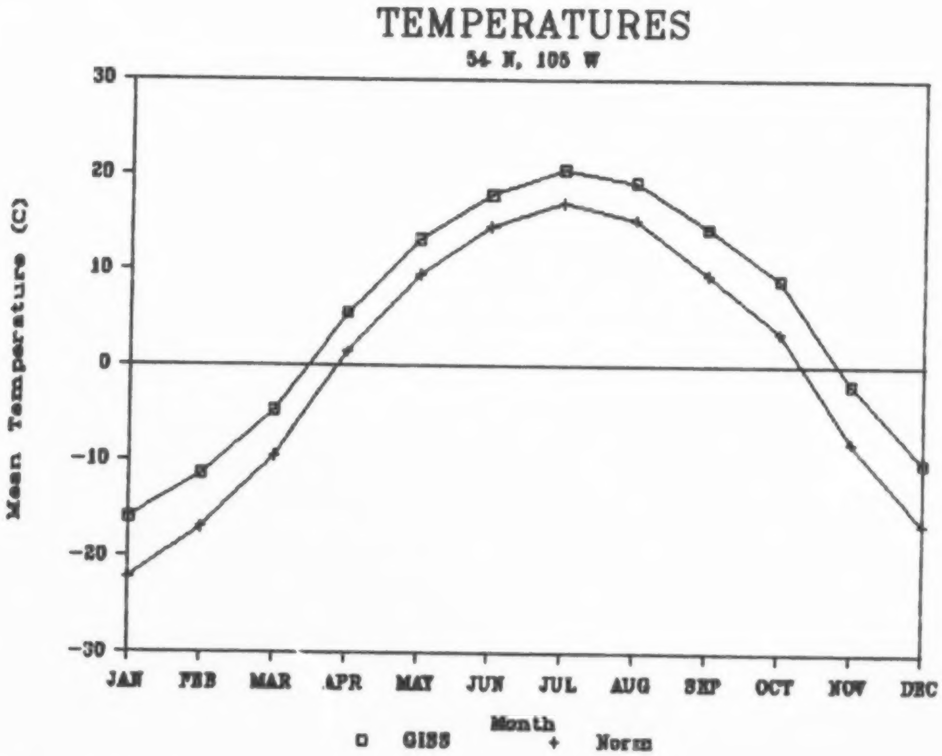


Figure C.1b Comparison of 1951-80 Normal (HIST) Monthly Temperatures with GISS Climatic Change Scenario Monthly Mean Temperatures for a Specified Gridpoint.

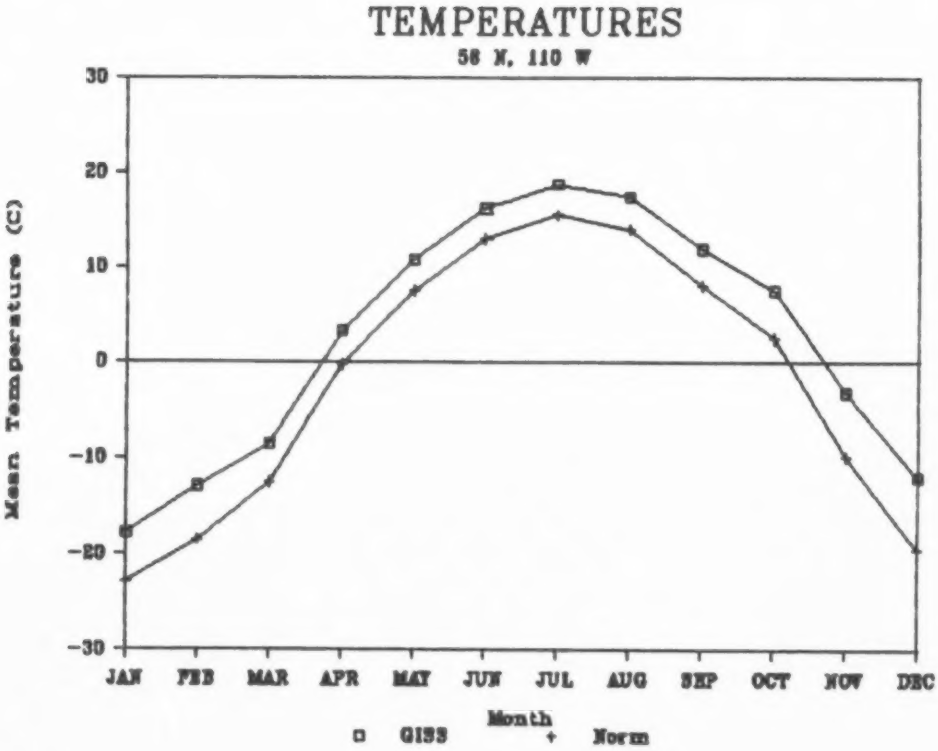


Figure C.1c Comparison of 1951-80 Normal (HIST) Monthly Temperatures with GISS Climatic Change Scenario Monthly Mean Temperatures for a Specified Gridpoint.

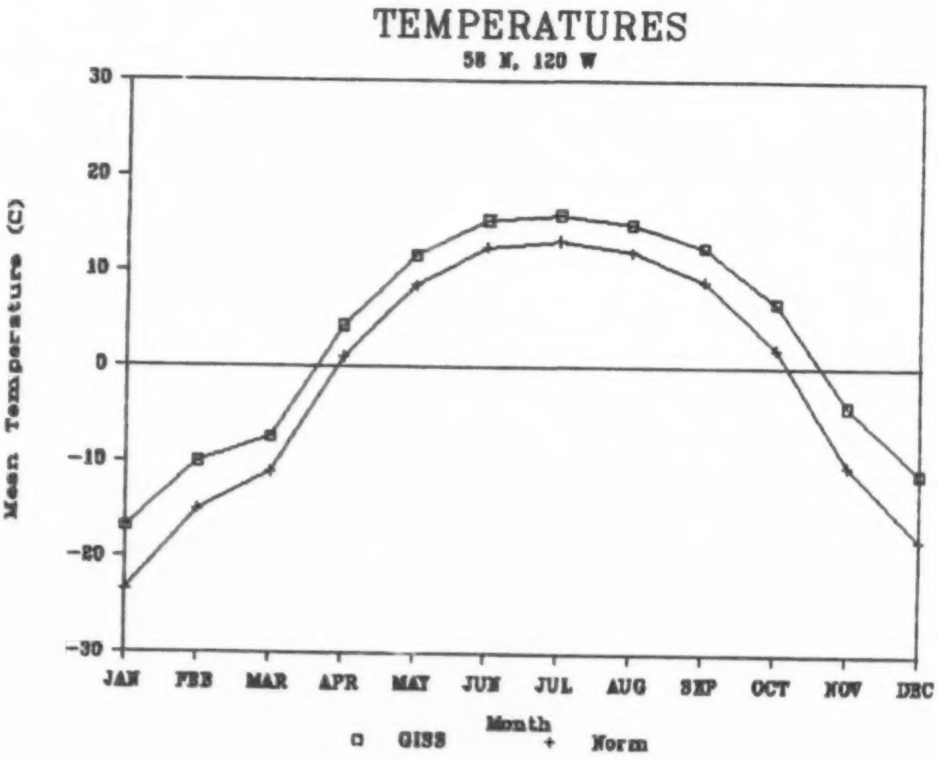


Figure C.1d Comparison of 1951-80 Normal (HIST) Monthly Temperatures with GISS Climatic Change Scenario Monthly Mean Temperatures for a Specified Gridpoint.

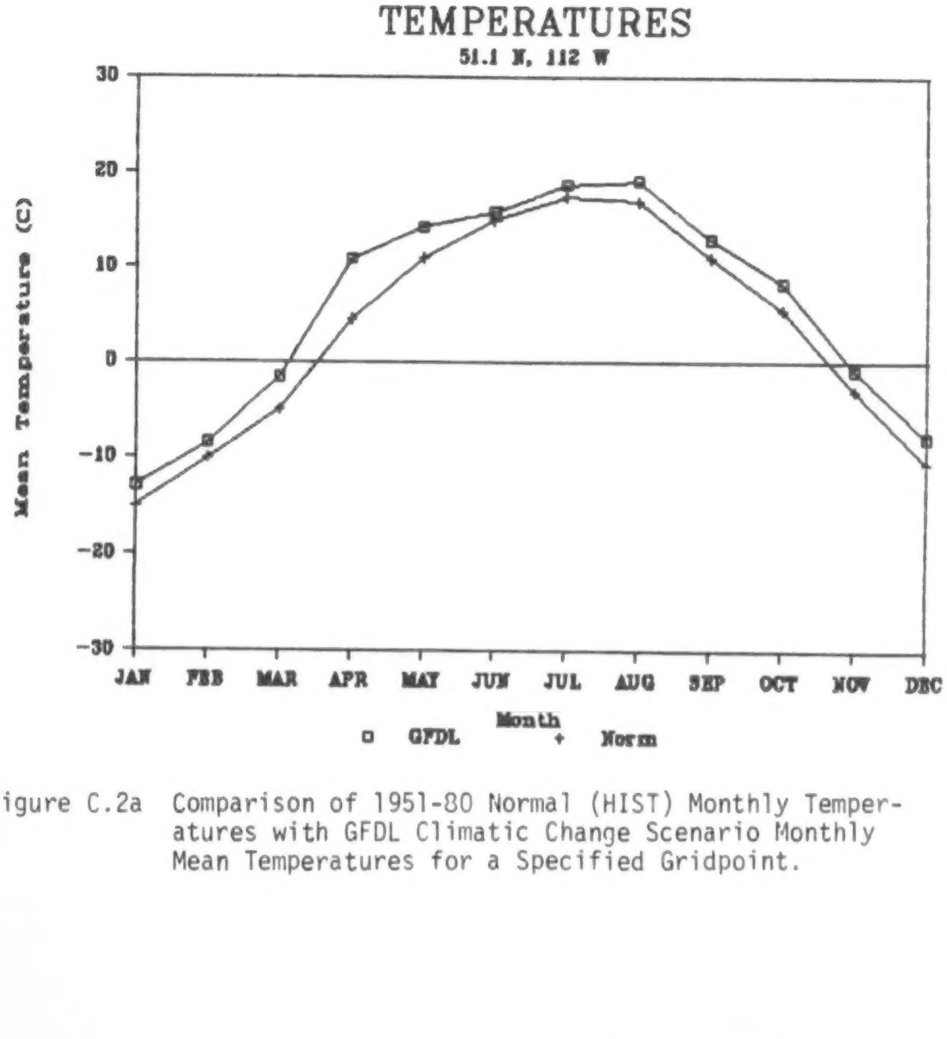


Figure C.2a Comparison of 1951-80 Normal (HIST) Monthly Temperatures with GFDL Climatic Change Scenario Monthly Mean Temperatures for a Specified Gridpoint.

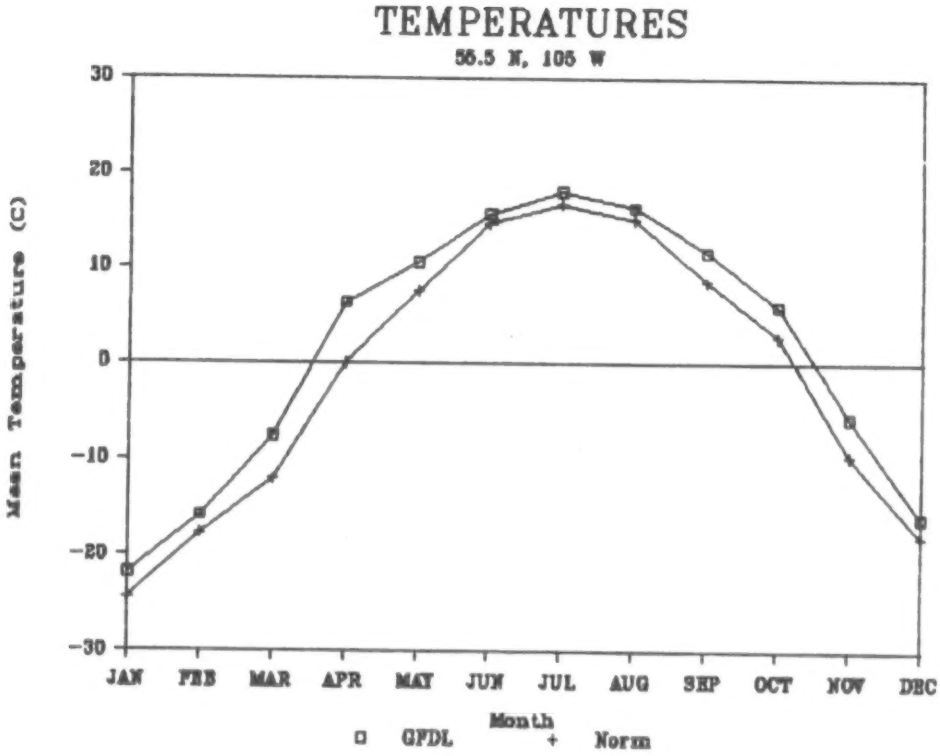


Figure C.2b Comparison of 1951-80 Normal (HIST) Monthly Temperatures with GFDL Climatic Change Scenario Monthly Mean Temperatures for a Specified Gridpoint.

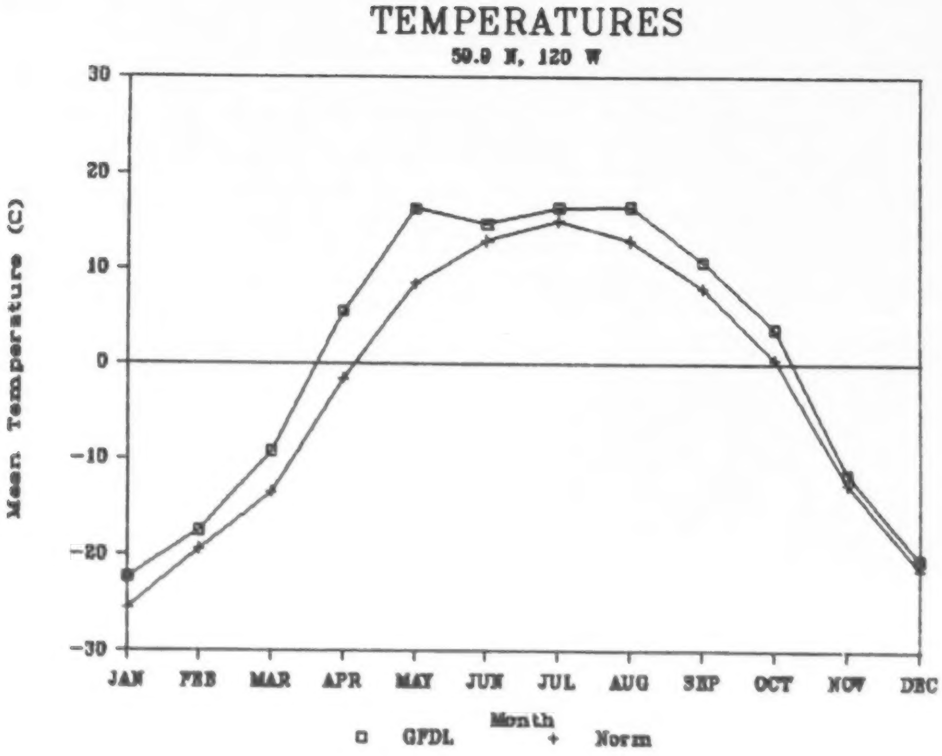


Figure C.2c Comparison of 1951-80 Normal (HIST) Monthly Temperatures with GFDL Climatic Change Scenario Monthly Mean Temperatures for a Specified Gridpoint.

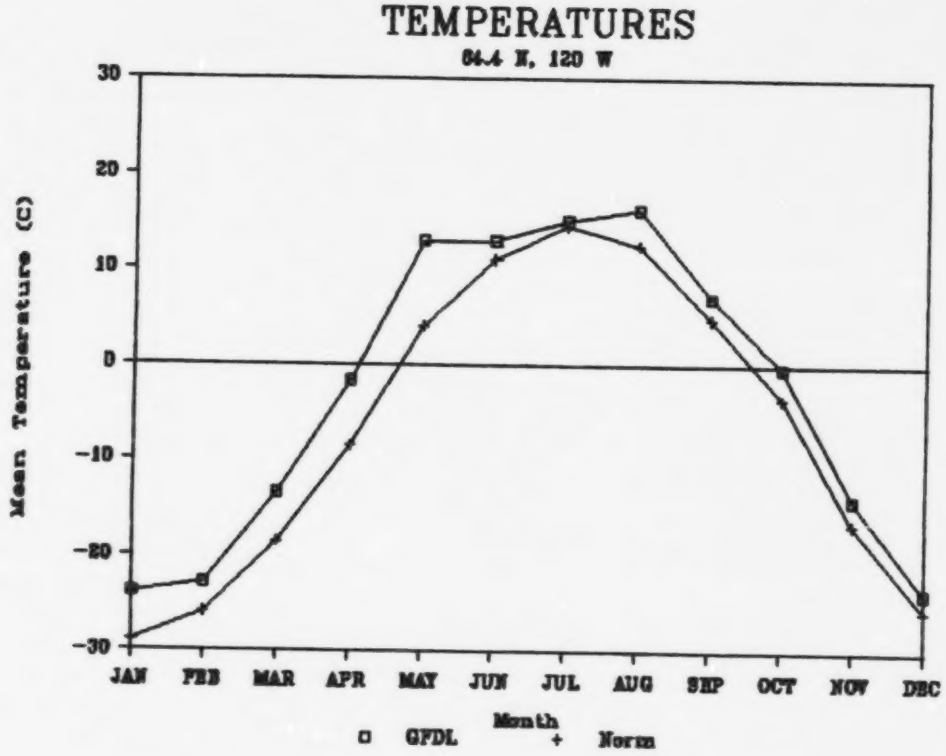
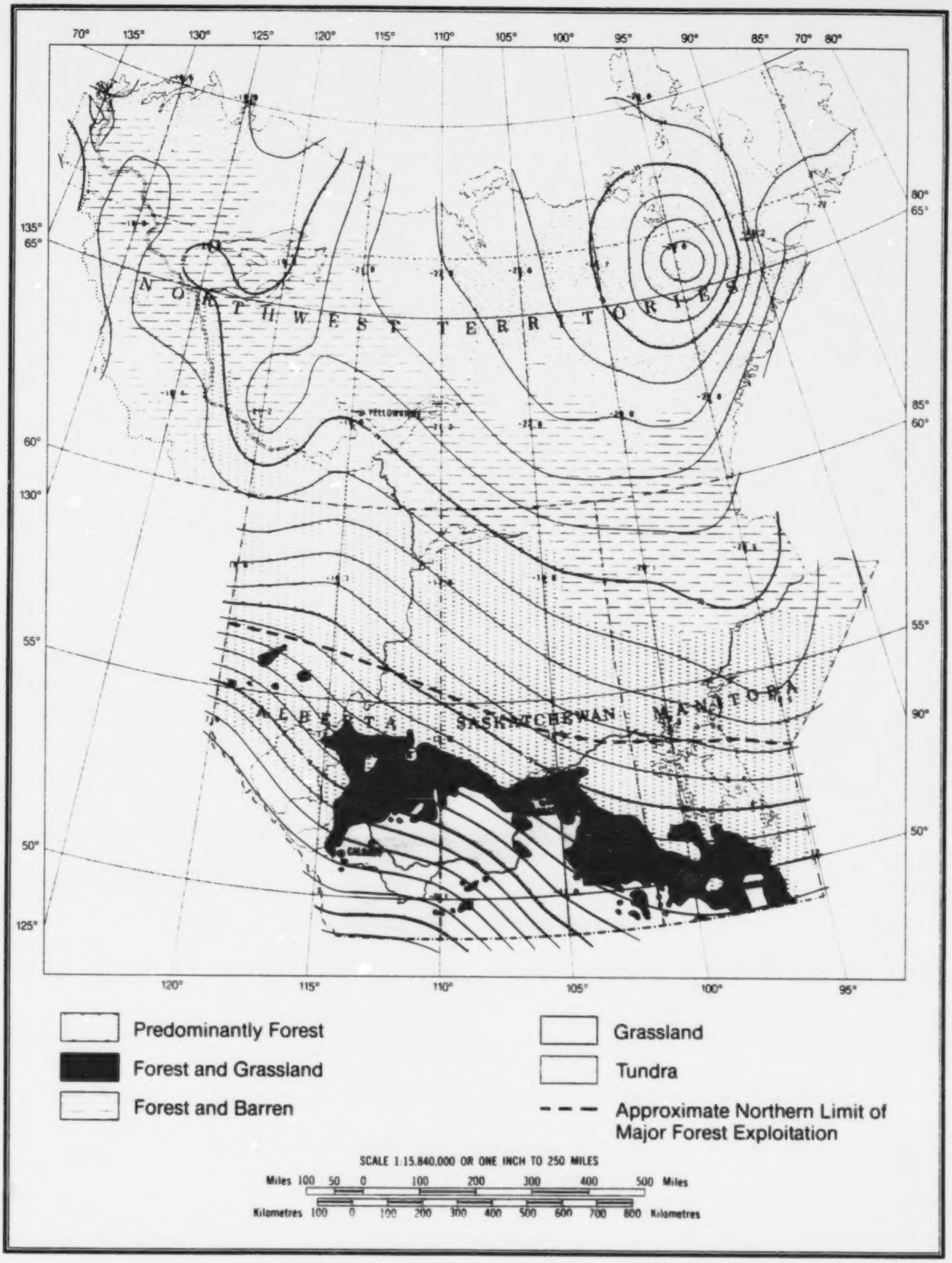


Figure C.2d Comparison of 1951-80 Normal (HIST) Monthly Temperatures with GFDL Climatic Change Scenario Monthly Mean Temperatures for a Specified Gridpoint.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Predominantly Forest
Forest and Grassland
Forest and Barren
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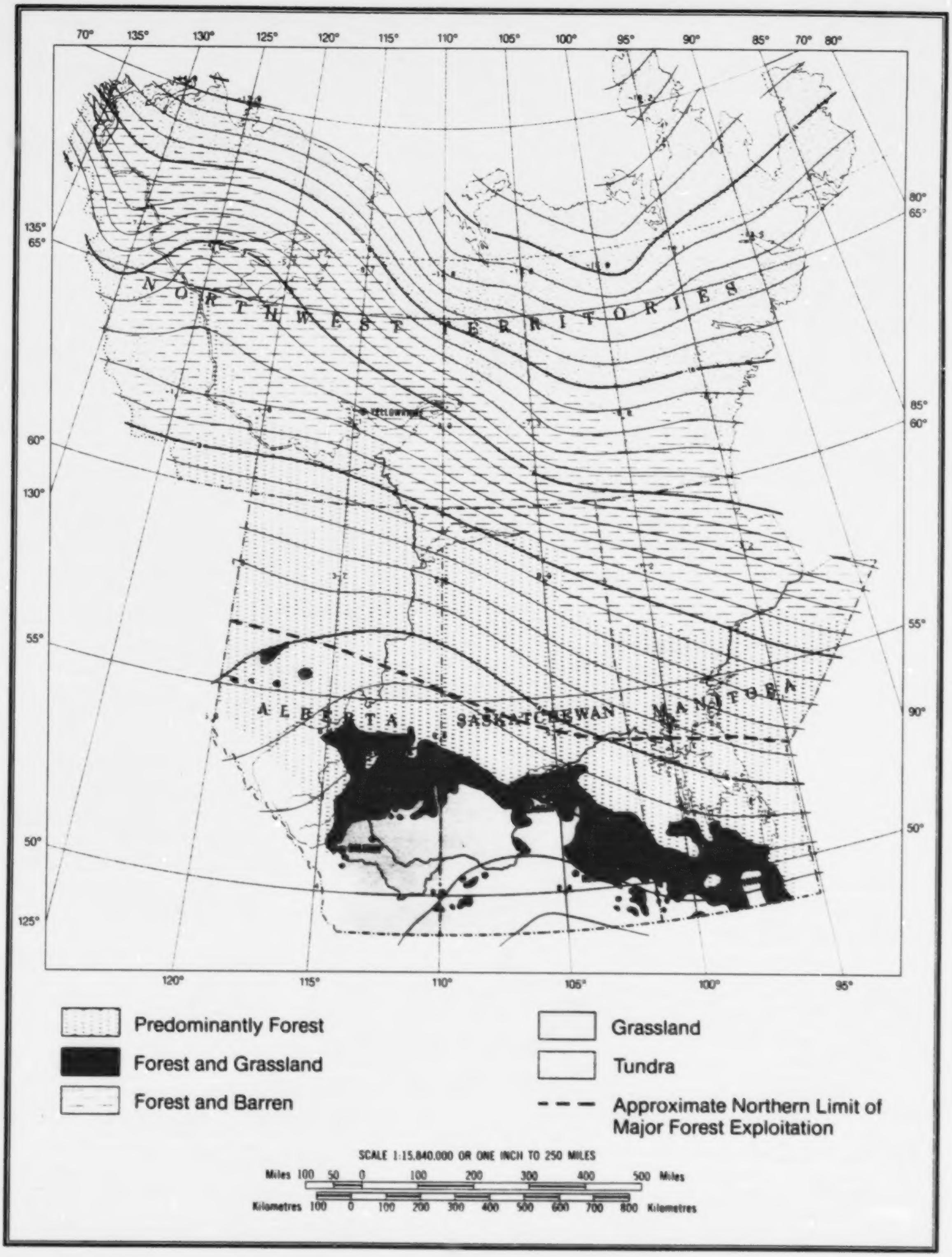
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.3a Spatial Patterns of Monthly Mean Temperatures for the GISS Climatic Change Scenario for January.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Predominantly Forest
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SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
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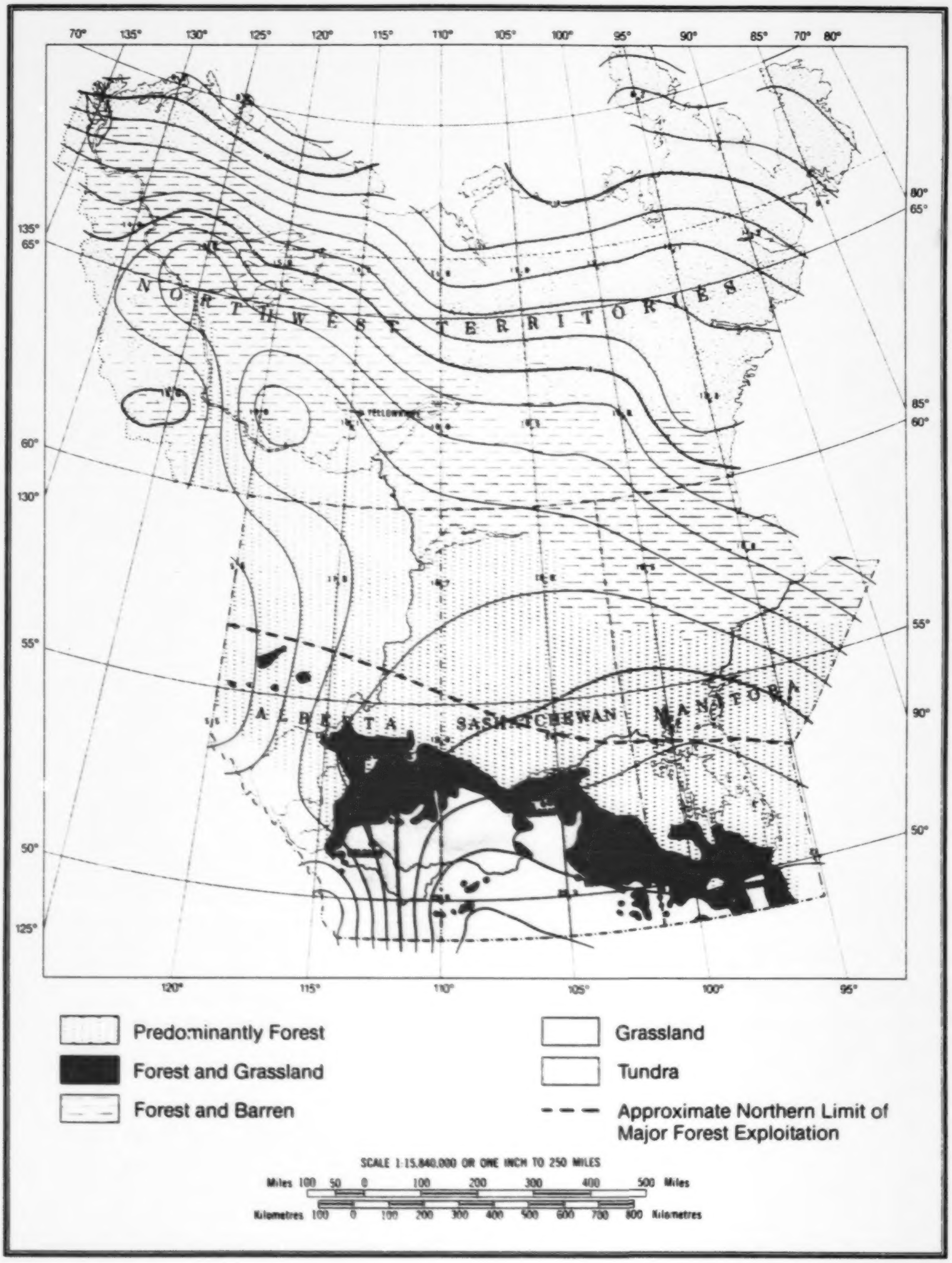
Figure C.3b Spatial Patterns of Monthly Mean Temperatures for the GISS Climatic Change Scenario for April.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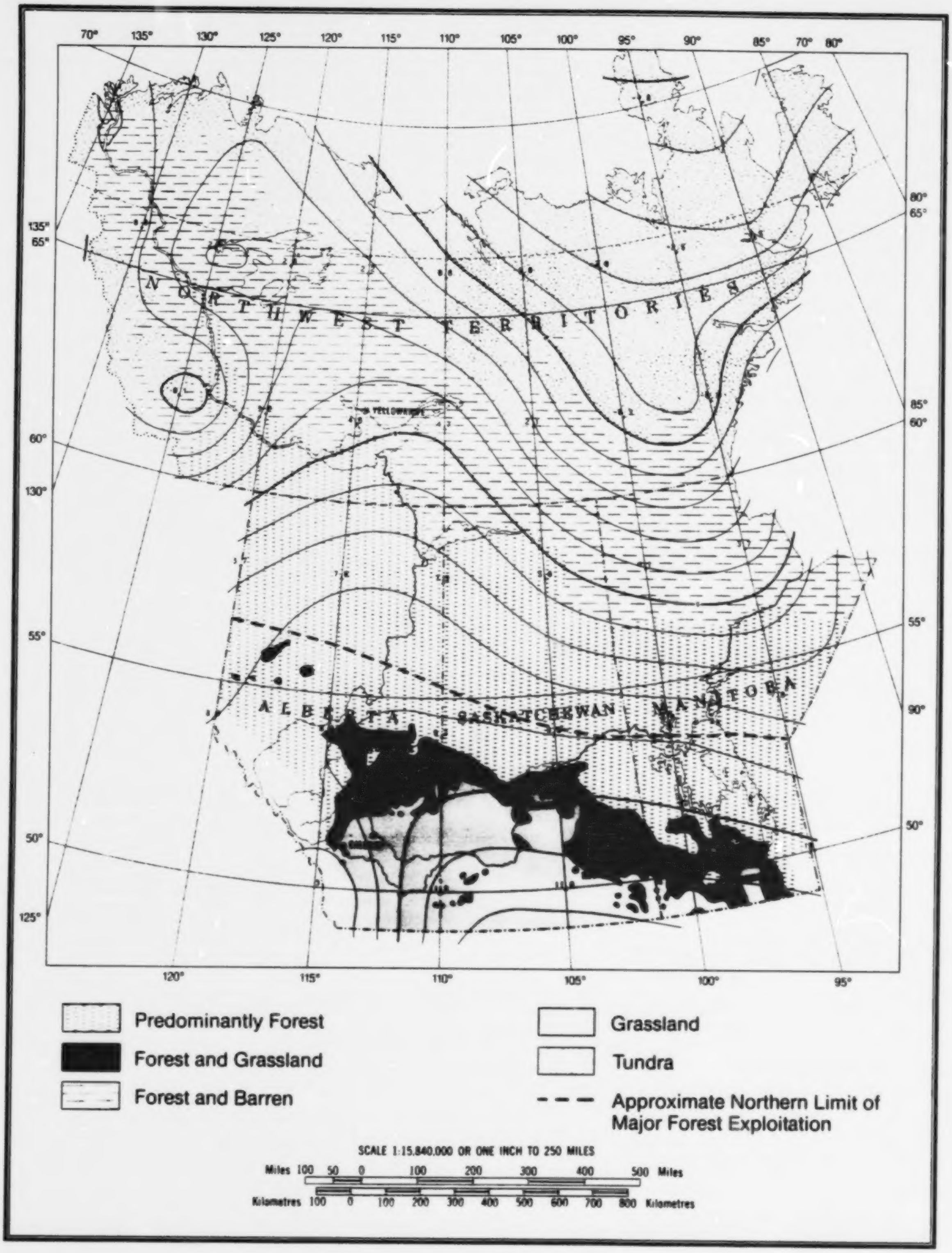
MANITOBA
Predominantly Forest
Grassland
Forest and Grassland
Tundra
Forest and Barren
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.3c Spatial Patterns of Monthly Mean Temperatures for the GISS Climatic Change Scenario for July.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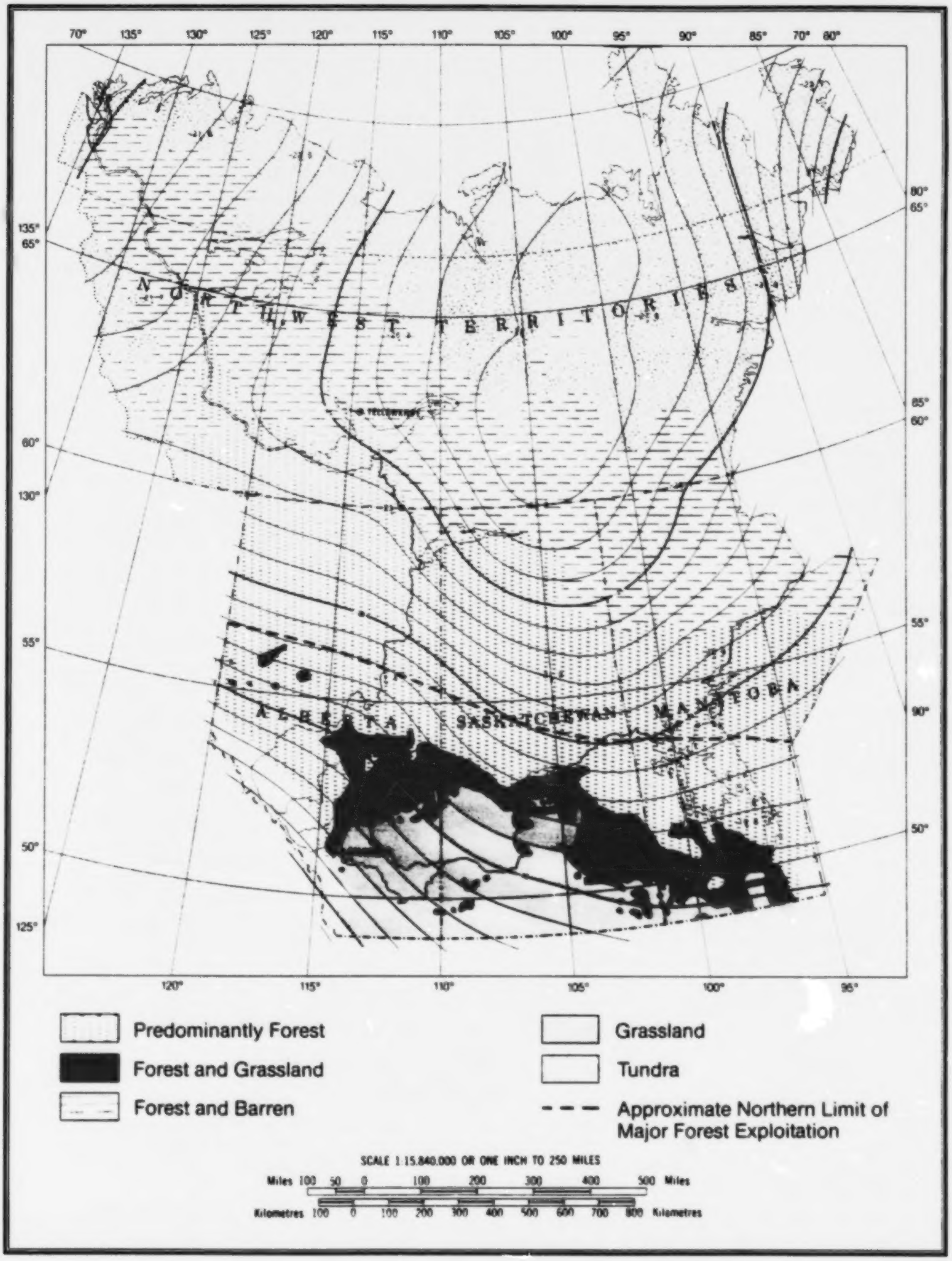
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.3d Spatial Patterns of Monthly Mean Temperatures for the GISS Climatic Change Scenario for October.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SASKATCHEWAN
MANITOBA
Predominantly Forest
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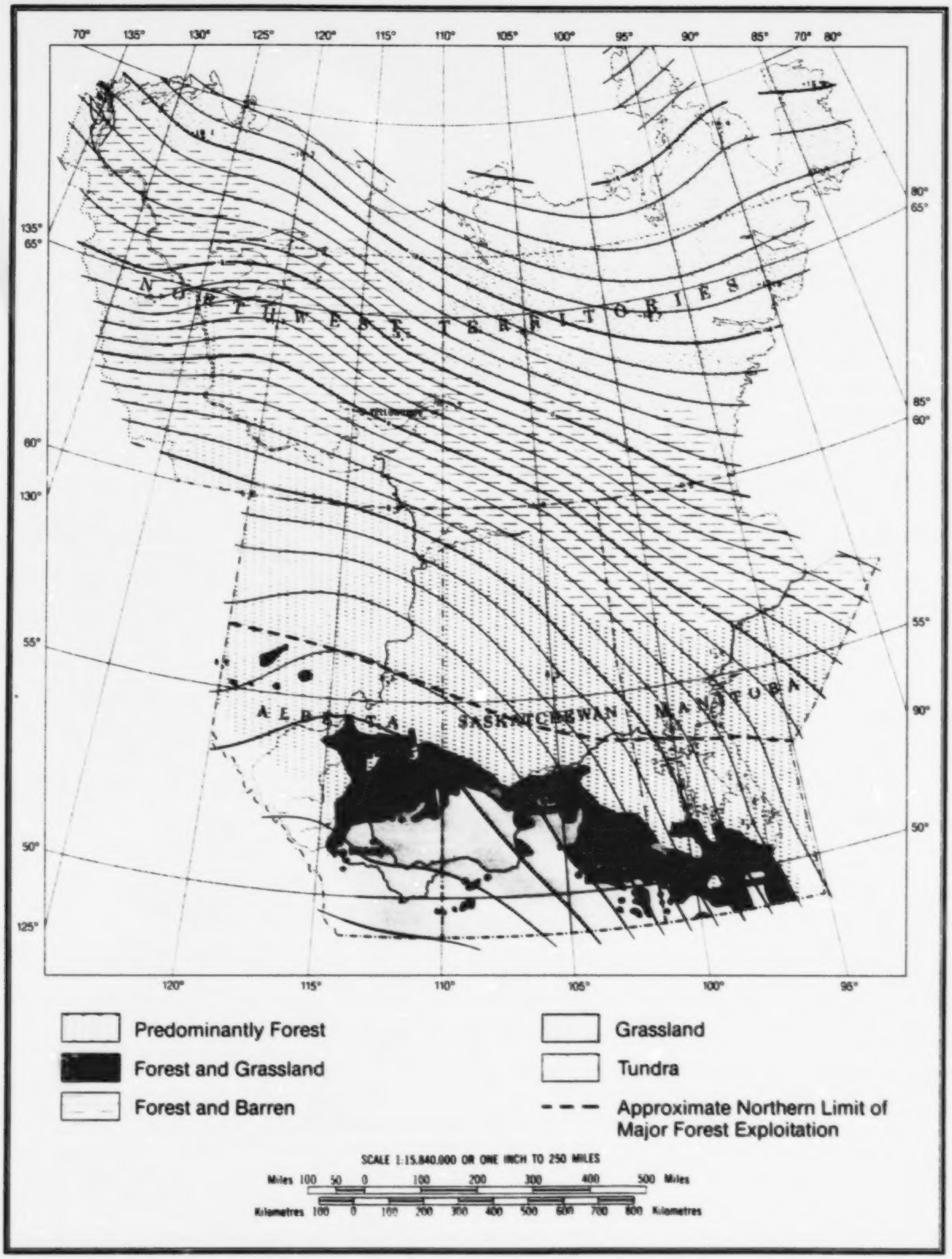
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.4a Spatial Patterns of Monthly Mean Temperatures for the GFDL Climatic Change Scenario for January.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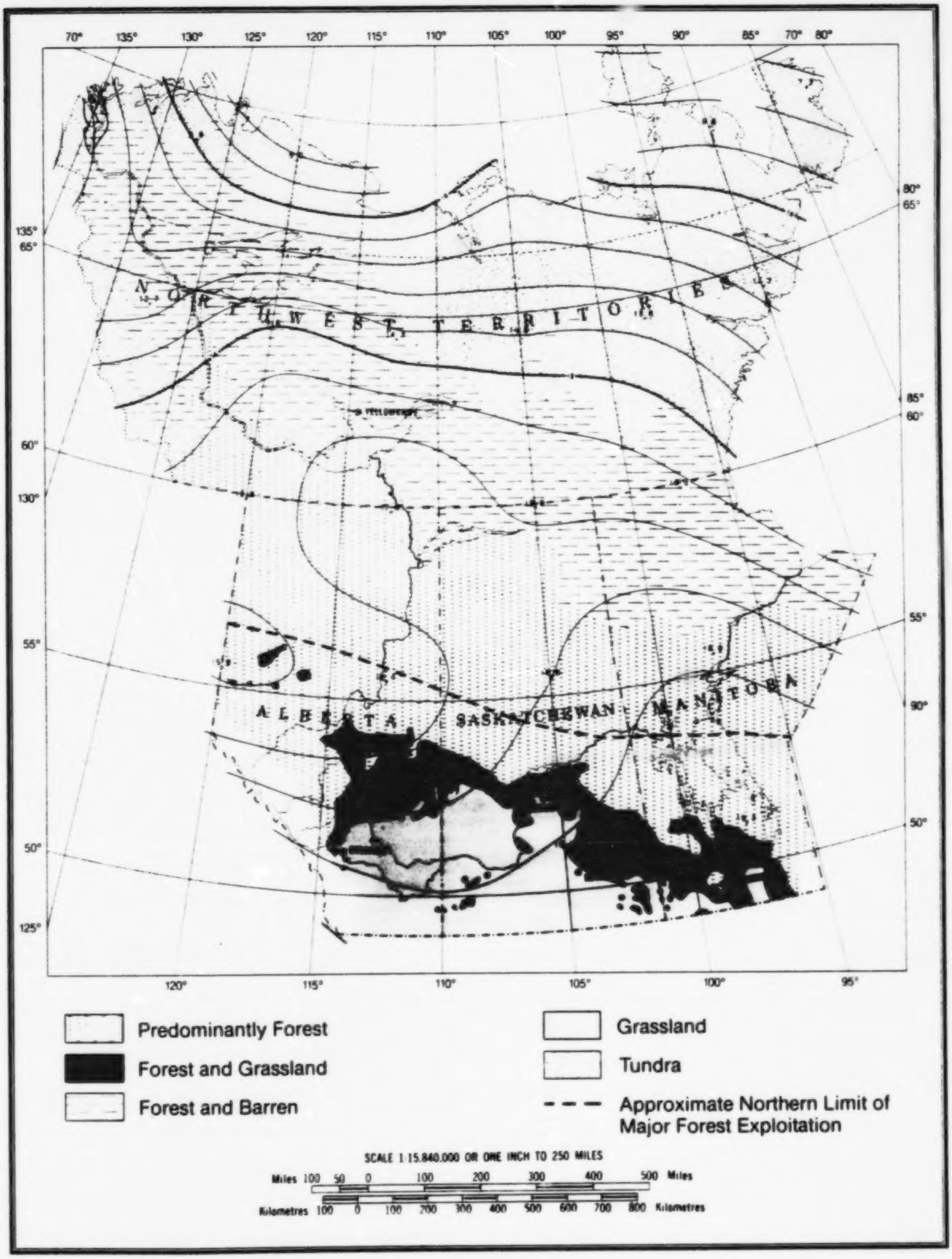
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.4b Spatial Patterns of Monthly Mean Temperatures for the GFDL Climatic Change Scenario for April.


NORTHWEST TERRITORIES
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Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
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Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres
70° 135° 130° 125° 120° 115° 110° 105° 100° 95° 90° 85° 70° 80°
120° 115° 110° 105° 100° 95°
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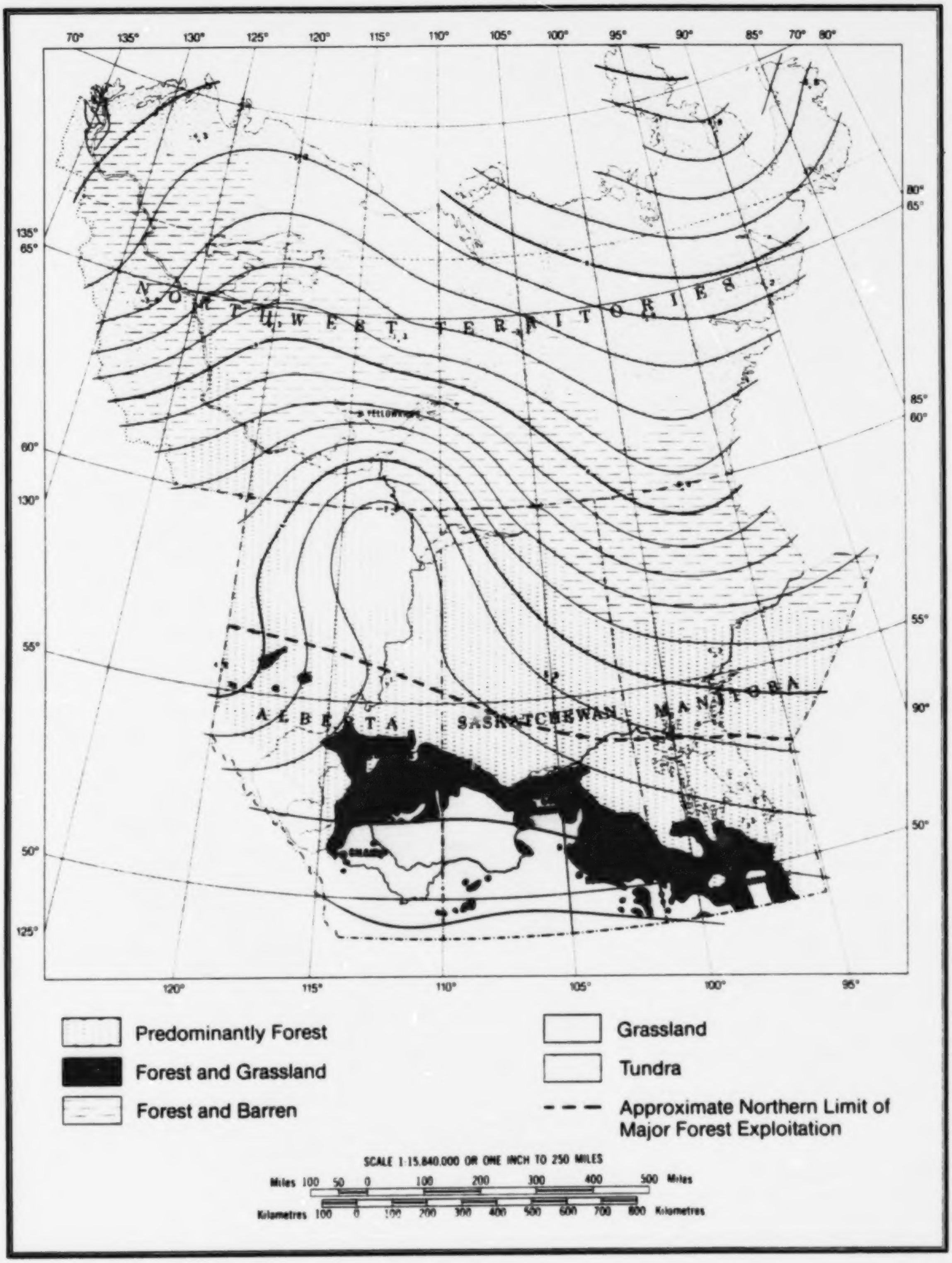
Figure C.4c Spatial Patterns of Monthly Mean Temperatures for the GFDL Climatic Change Scenario for July.


NORTHWEST TERRITORIES
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65° 60° 55° 50°
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.4d Spatial Patterns of Monthly Mean Temperatures for the GFDL Climatic Change Scenario for October.

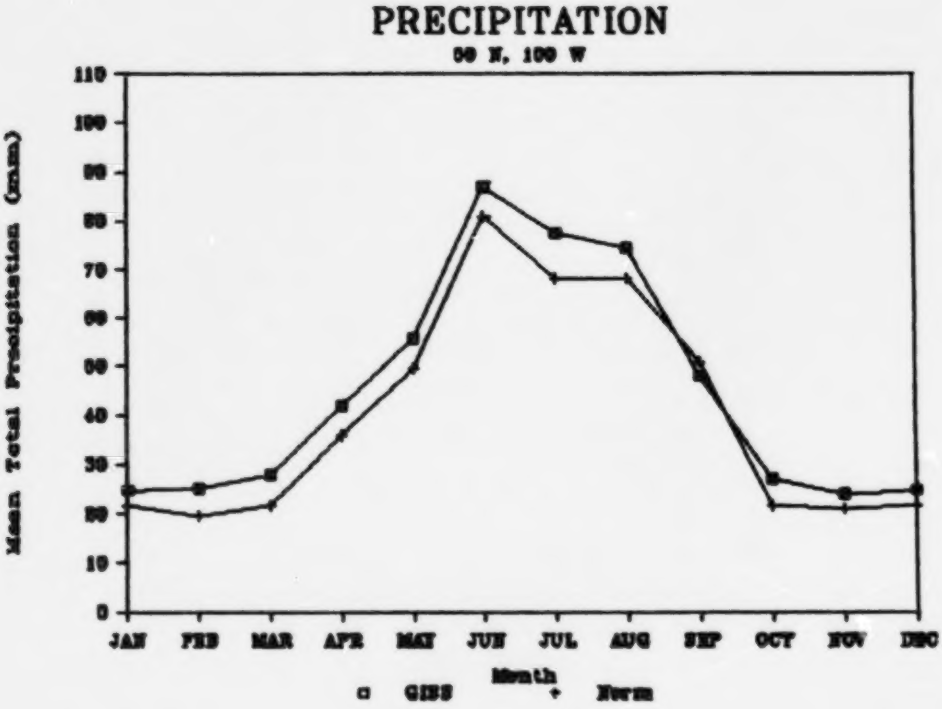


Figure C.5a Comparison of 1951-80 Normal (HIST) Monthly Precipitation Totals with GISS1 Climatic Change Scenario Monthly Mean Precipitation Totals for a Specified Gridpoint.

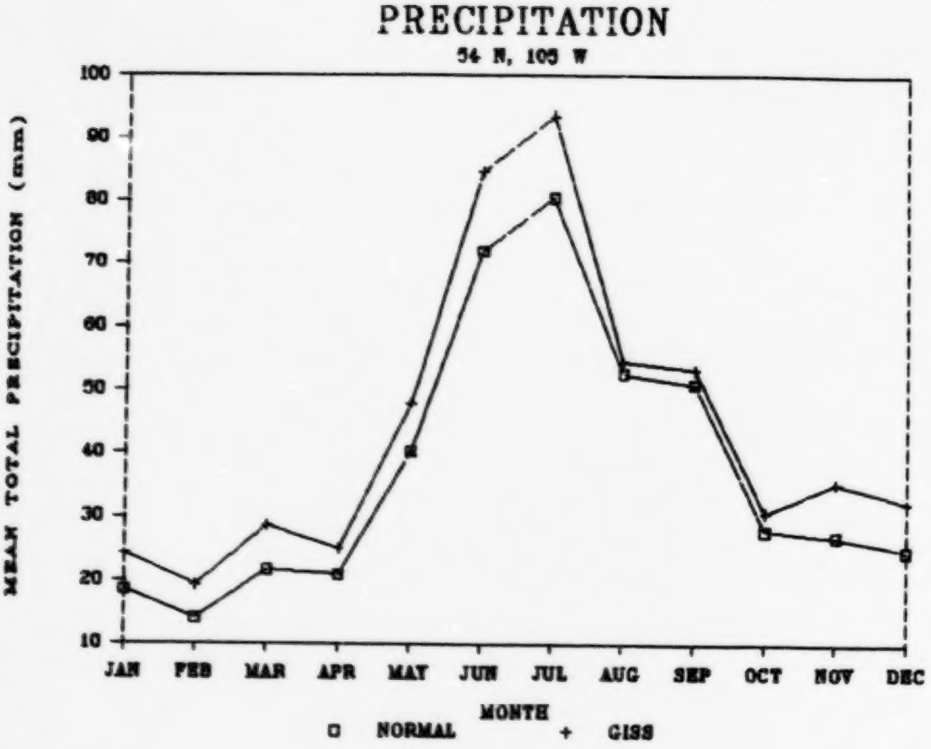


Figure C.5b Comparison of 1951-80 Normal (HIST) Monthly Precipitation Totals with GISS1 Climatic Change Scenario Monthly Mean Precipitation Totals for a Specified Gridpoint.

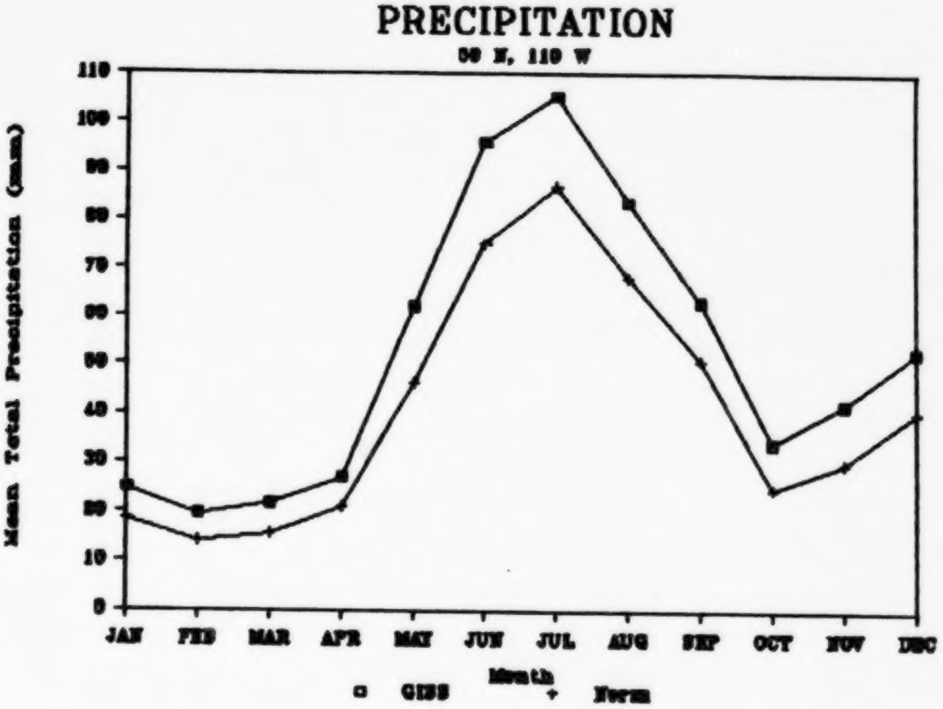


Figure C.5c Comparison of 1951-80 Normal (HIST) Monthly Precipitation Totals with GISS1 Climatic Change Scenario Monthly Mean Precipitation Totals for a Specified Gridpoint.

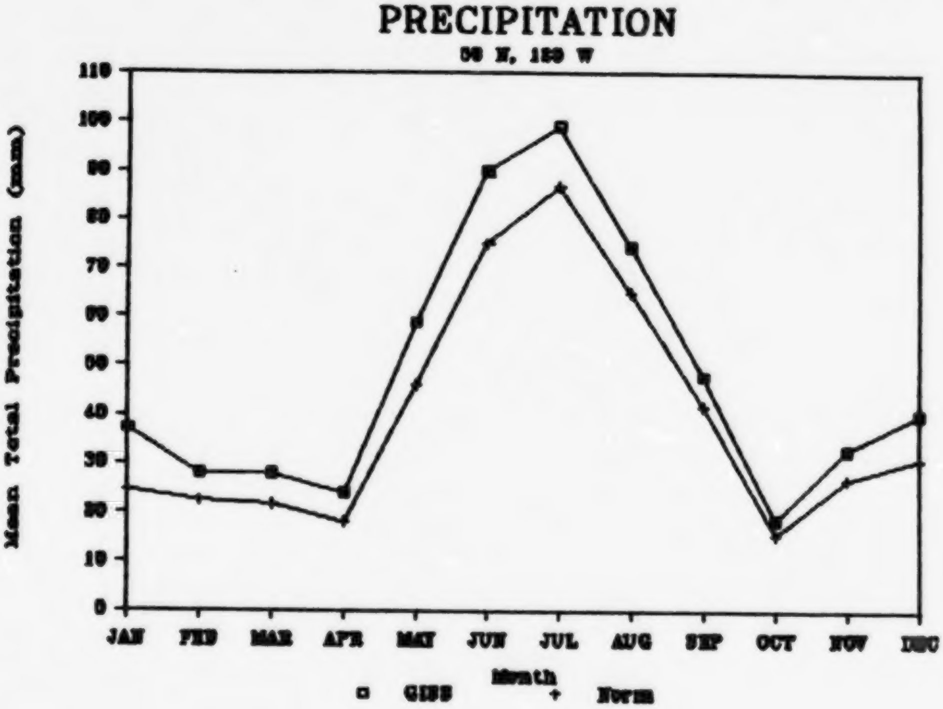


Figure C.5d Comparison of 1951-80 Normal (HIST) Monthly Precipitation Totals with GISS1 Climatic Change Scenario Monthly Mean Precipitation Totals for a Specified Gridpoint.

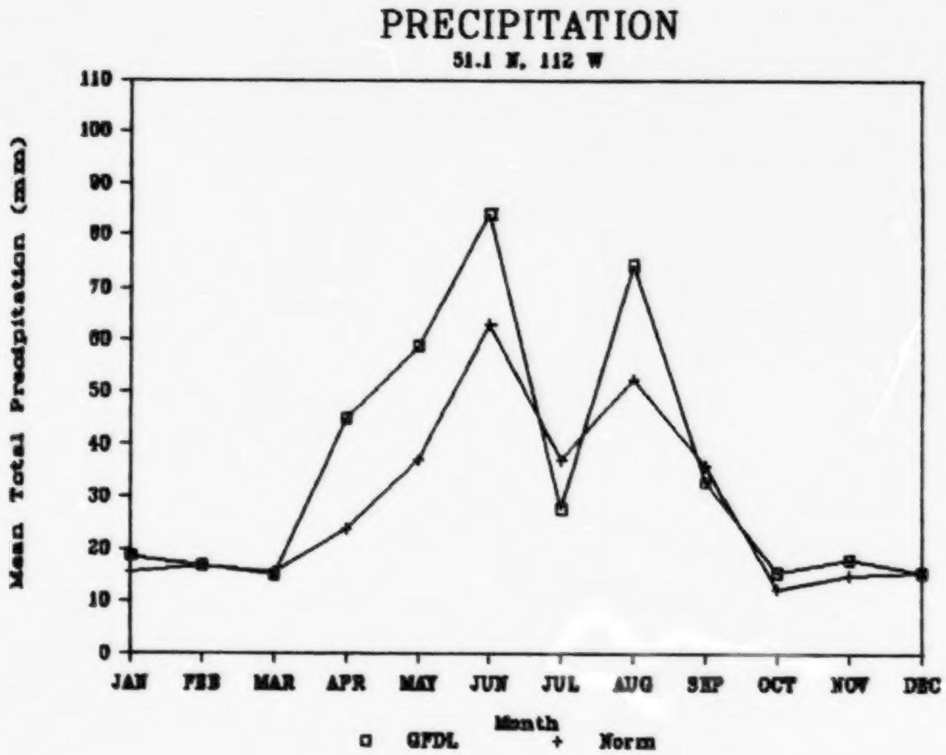


Figure C.6a Comparison of 1951-80 Normal (HIST) Monthly Precipitation Totals with GFDL1 Climatic Change Scenario Monthly Mean Precipitation Totals for a Specified Gridpoint.

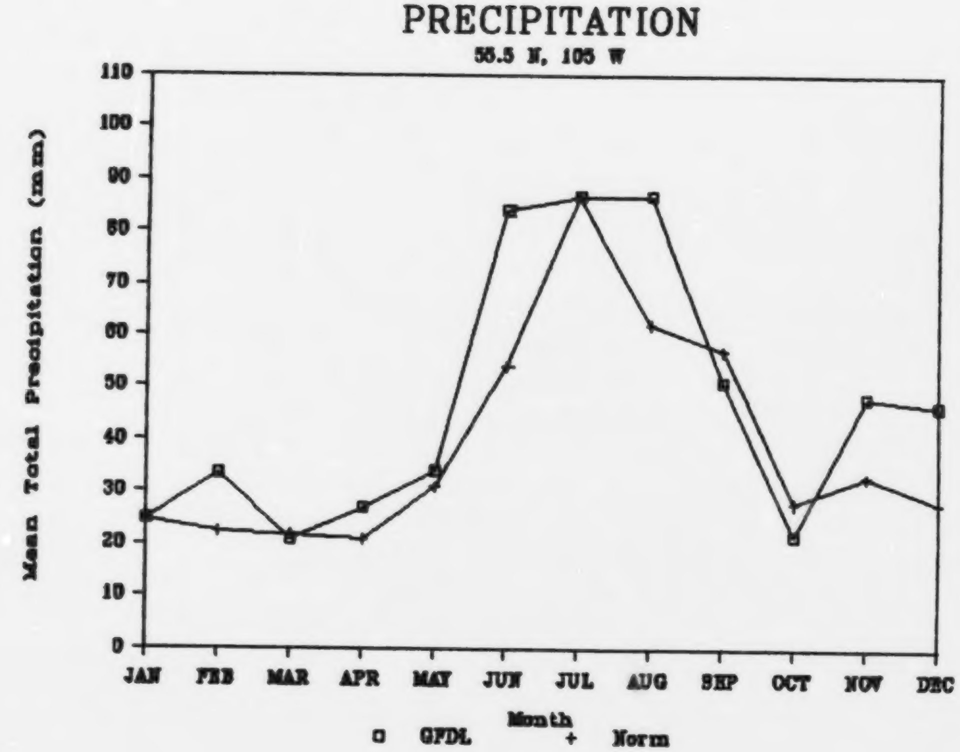


Figure C.6b Comparison of 1951-80 Normal (HIST) Monthly Precipitation Totals with GFDL1 Climatic Change Scenario Monthly Mean Precipitation Totals for a Specified Gridpoint.

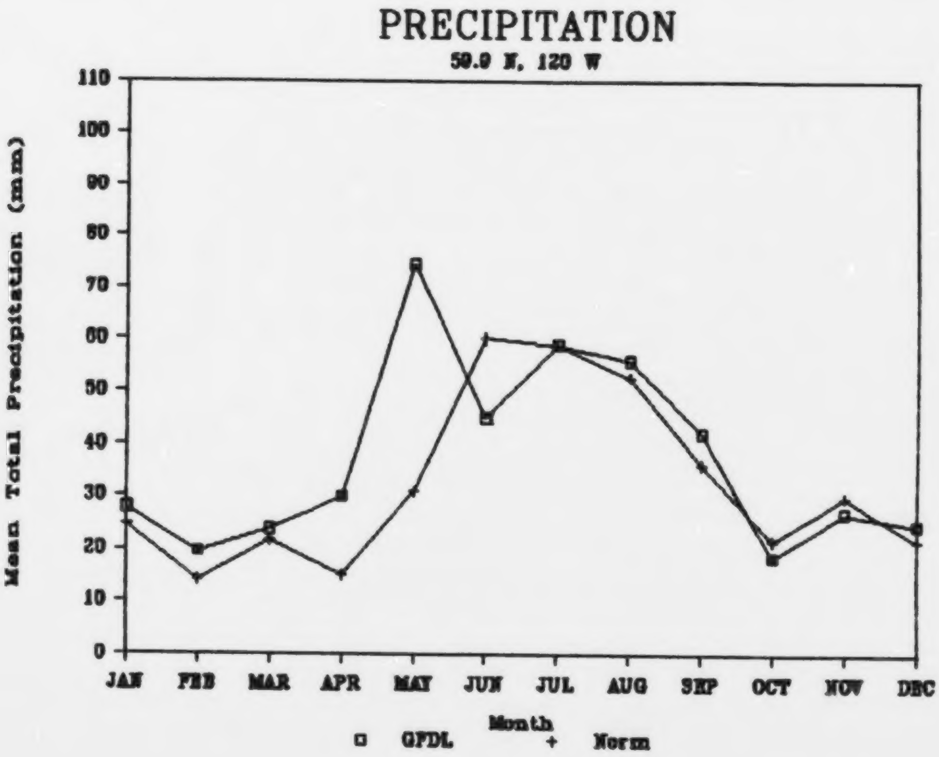


Figure C.6c Comparison of 1951-80 Normal (HIST) Monthly Precipitation Totals with GFDL1 Climatic Change Scenario Monthly Mean Precipitation Totals for a Specified Gridpoint.

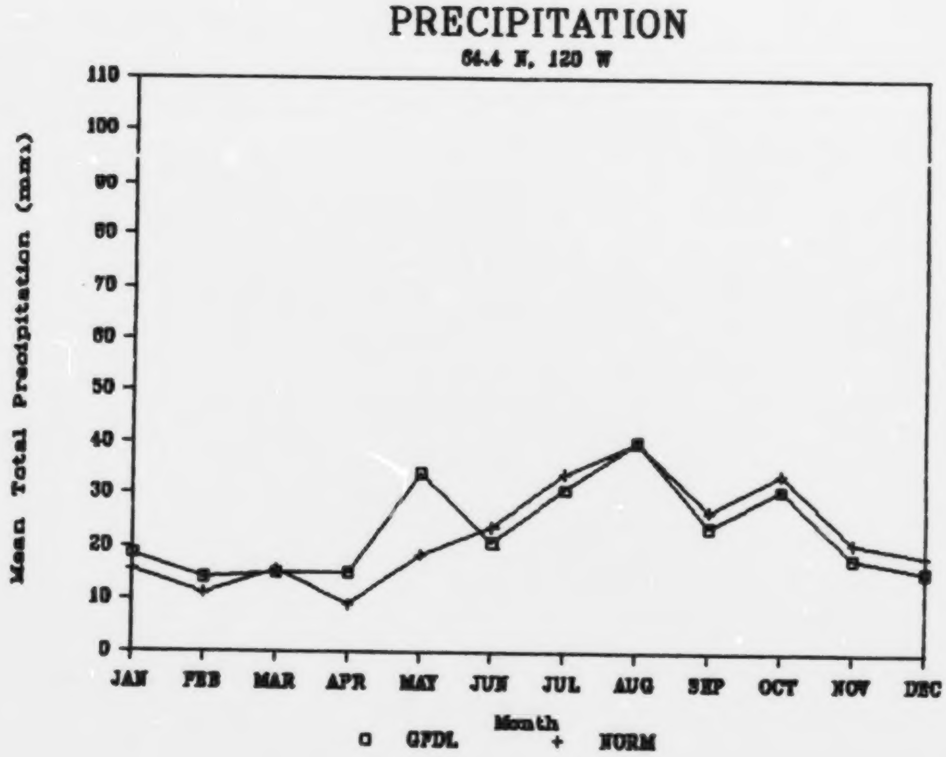
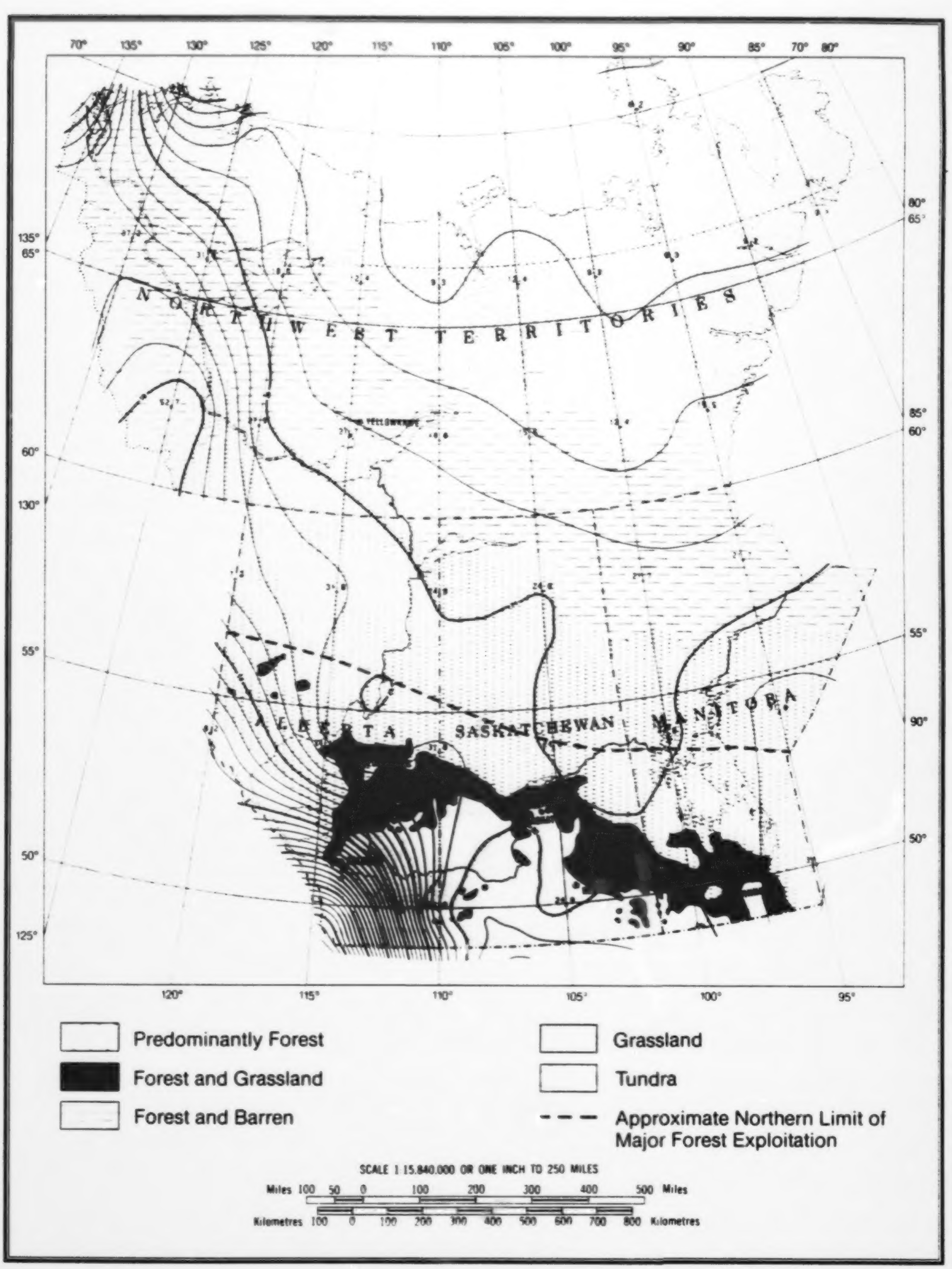


Figure C.6d Comparison of 1951-80 Normal (HIST) Monthly Precipitation Totals with GFDL1 Climatic Change Scenario Monthly Mean Precipitation Totals for a Specified Gridpoint.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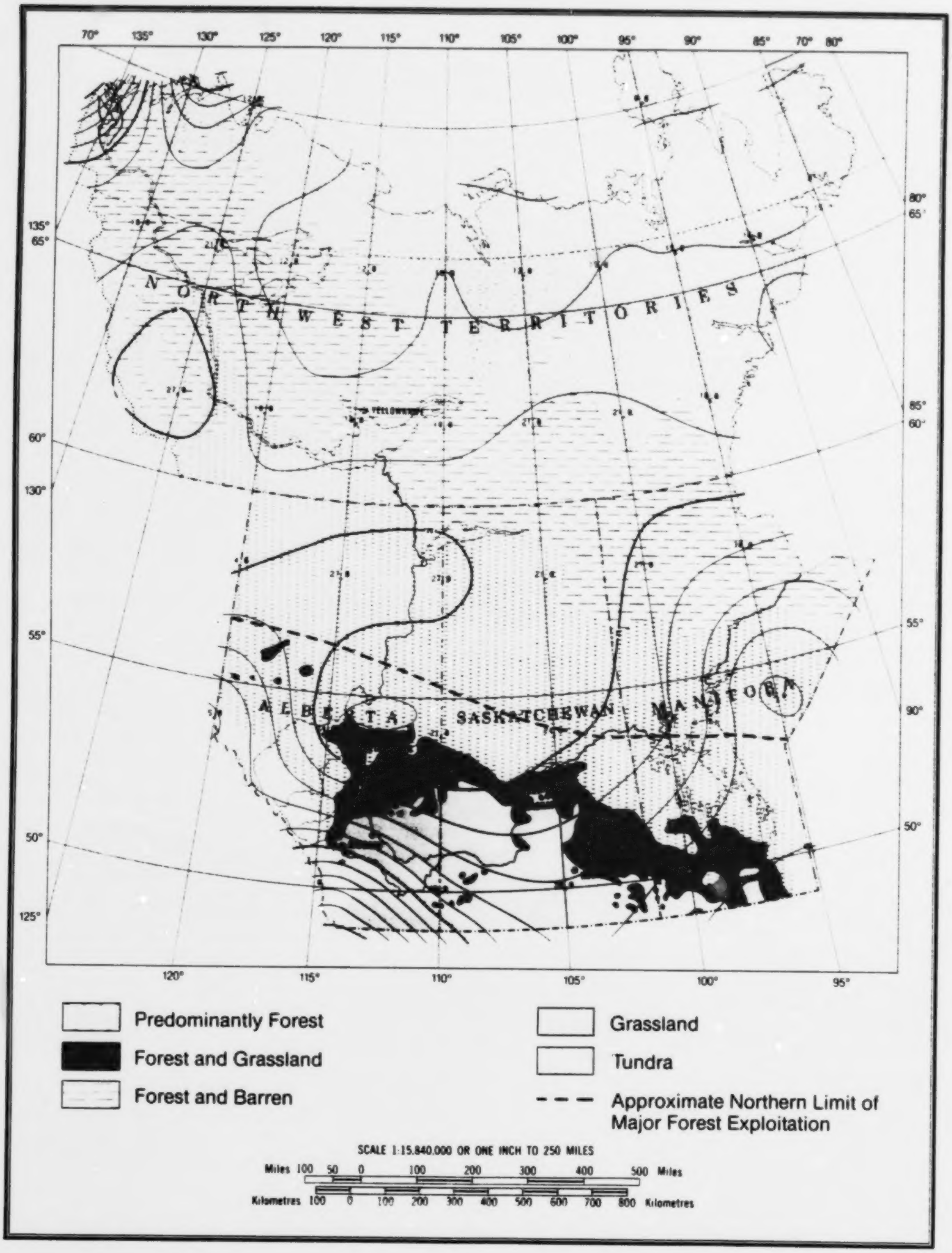
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.7a Spatial Patterns of Monthly Mean Precipitation Totals for the GISS1 Climatic Change Scenario for January.


NORTHWEST TERRITORIES
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Forest and Barren
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Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
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135° 65° 60° 130° 55° 50° 125°
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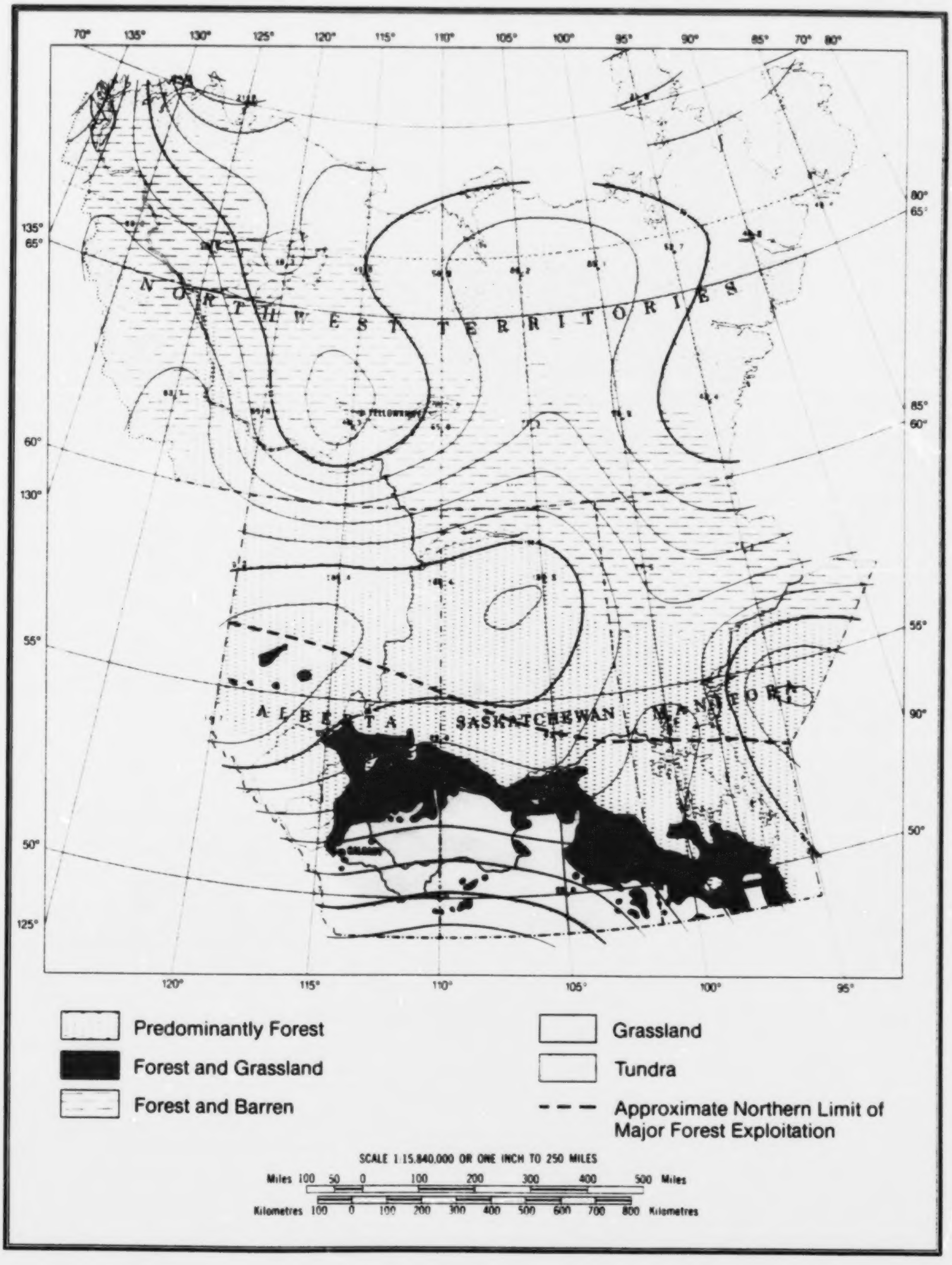
Figure C.7b Spatial Patterns of Monthly Mean Precipitation Totals for the GISS1 Climatic Change Scenario for April.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Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.7c Spatial Patterns of Monthly Mean Precipitation Totals for the GISS1 Climatic Change Scenario for July.

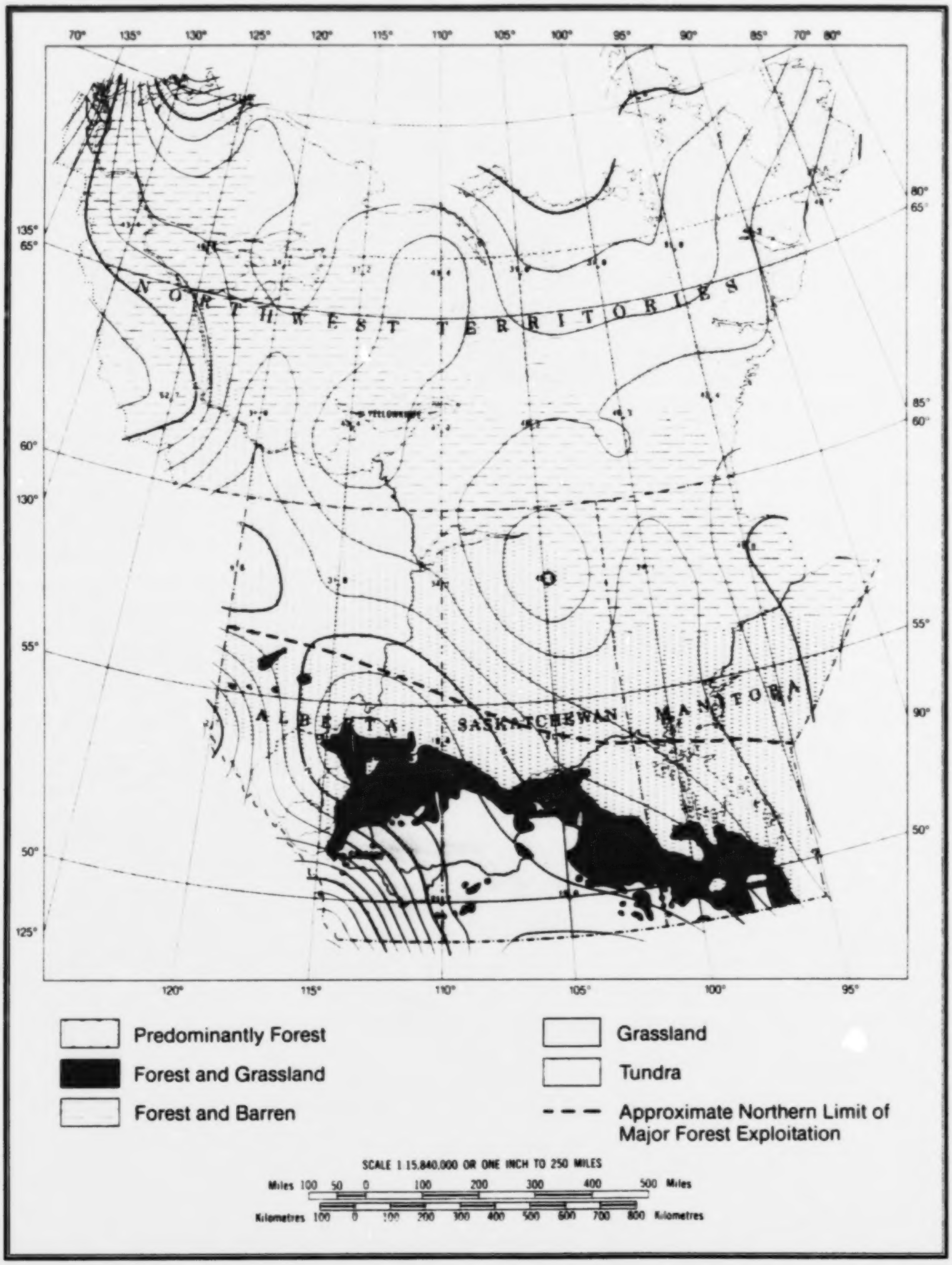

70°
135°
130°
125°
120°
115°
110°
105°
100°
95°
90°
85°
70°
80°
65°
60°
55°
50°
NORTHWEST TERRITORIES
YELLOWKNIFE
ALBERTA
SASKATCHEWAN
MANITOBA
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.7d Spatial Patterns of Monthly Mean Precipitation Totals for the GISS1 Climatic Change Scenario for October.

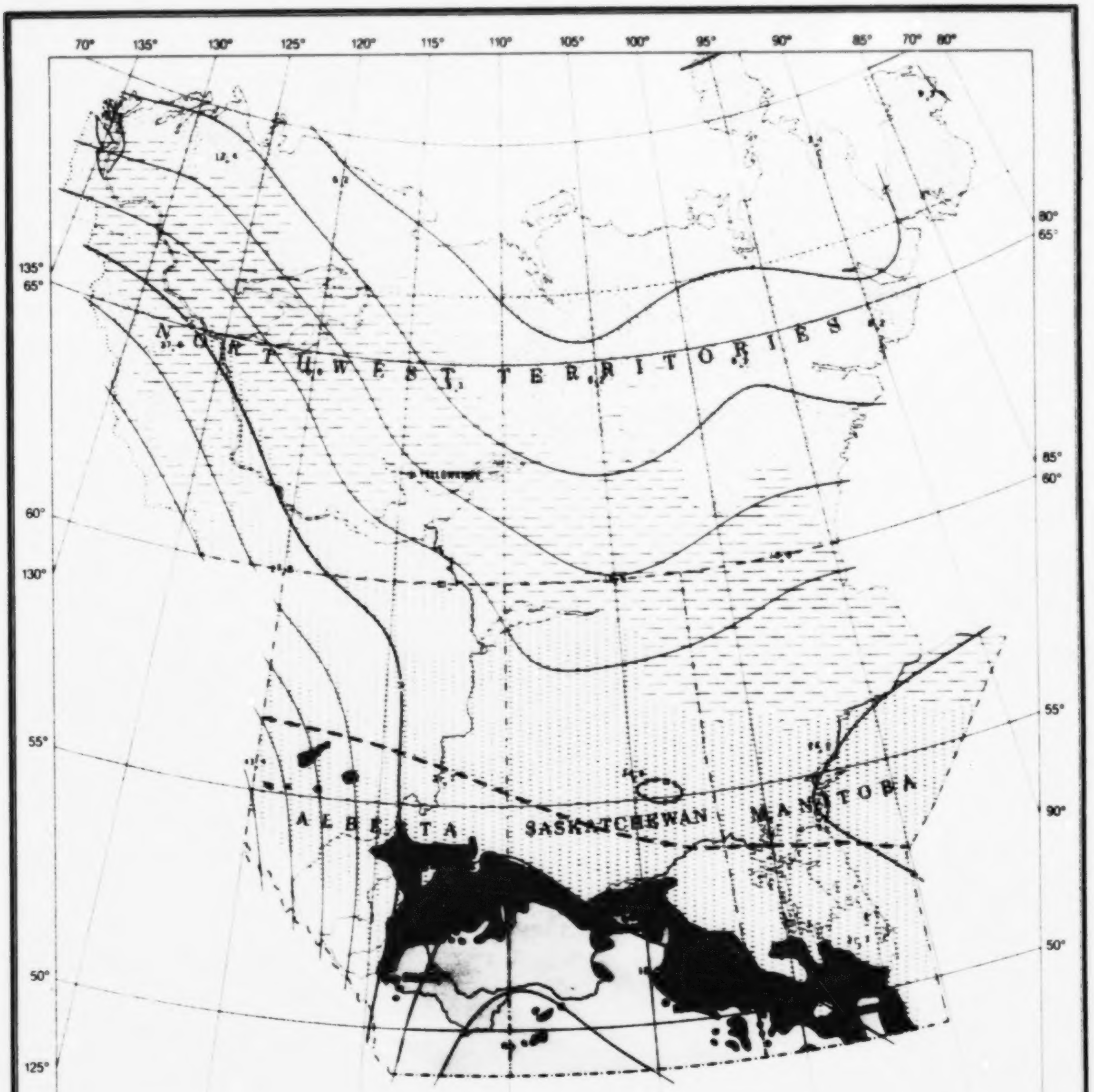
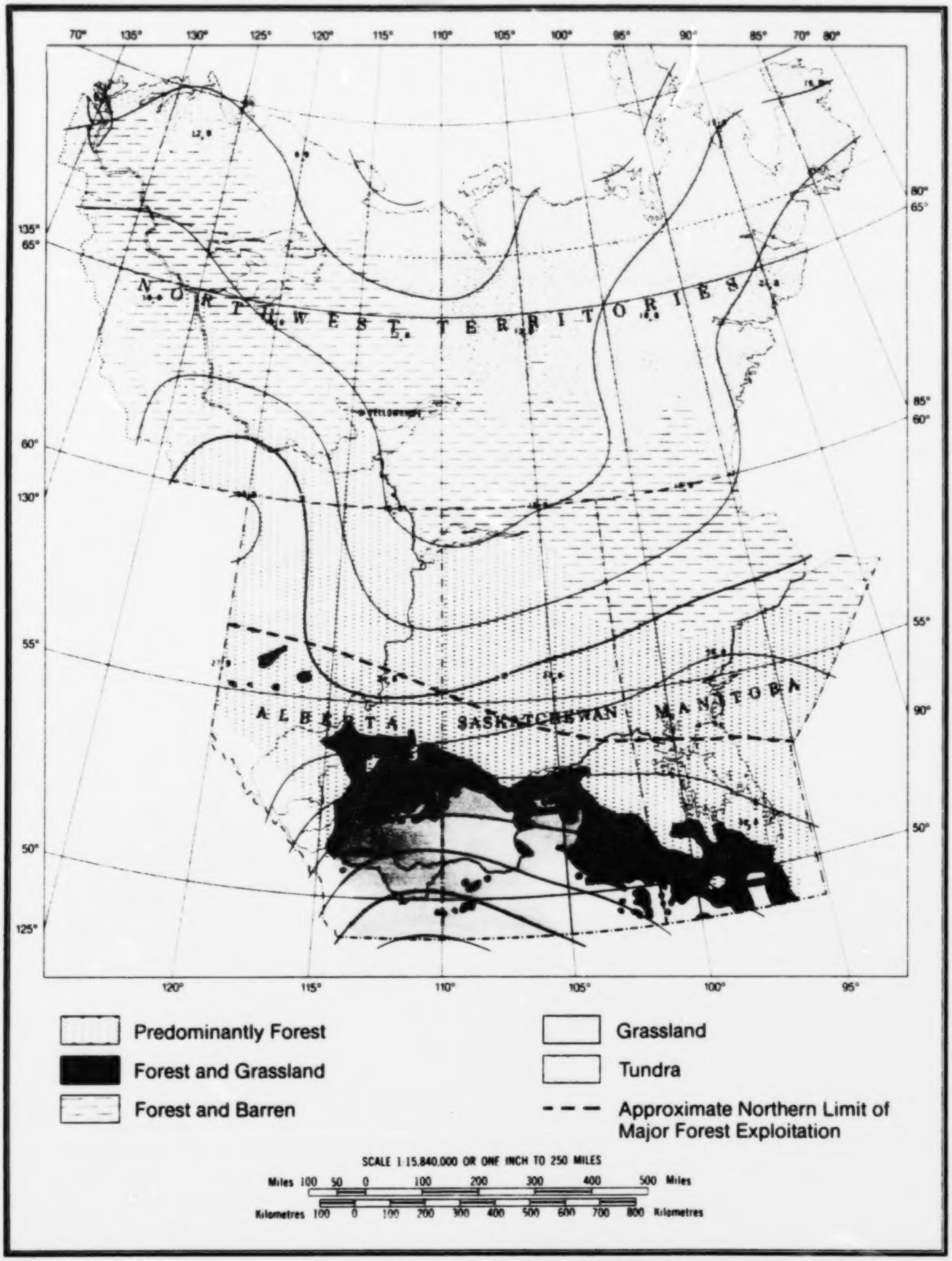

NORTHWEST TERRITORIES
ALBERTA
SASKATCHEWAN
MANITOBA
YELLOWKNIFE
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres
120° 115° 110° 105° 100° 95°
65° 60° 55° 50°

Figure C.8a Spatial Patterns of Monthly Mean Precipitation Totals for the GFDL1 Climatic Change Scenario for January.


70°
135°
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90°
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65°
60°
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125°
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60°
55°
90°
50°
N O R T H W E S T   T E R R I T O R I E S
ALBERTA
SASKATCHEWAN
MANITOBA
YELLOWKNIFE
120°
115°
110°
105°
100°
95°
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.8b Spatial Patterns of Monthly Mean Precipitation Totals for the GFDL1 Climatic Change Scenario for April.

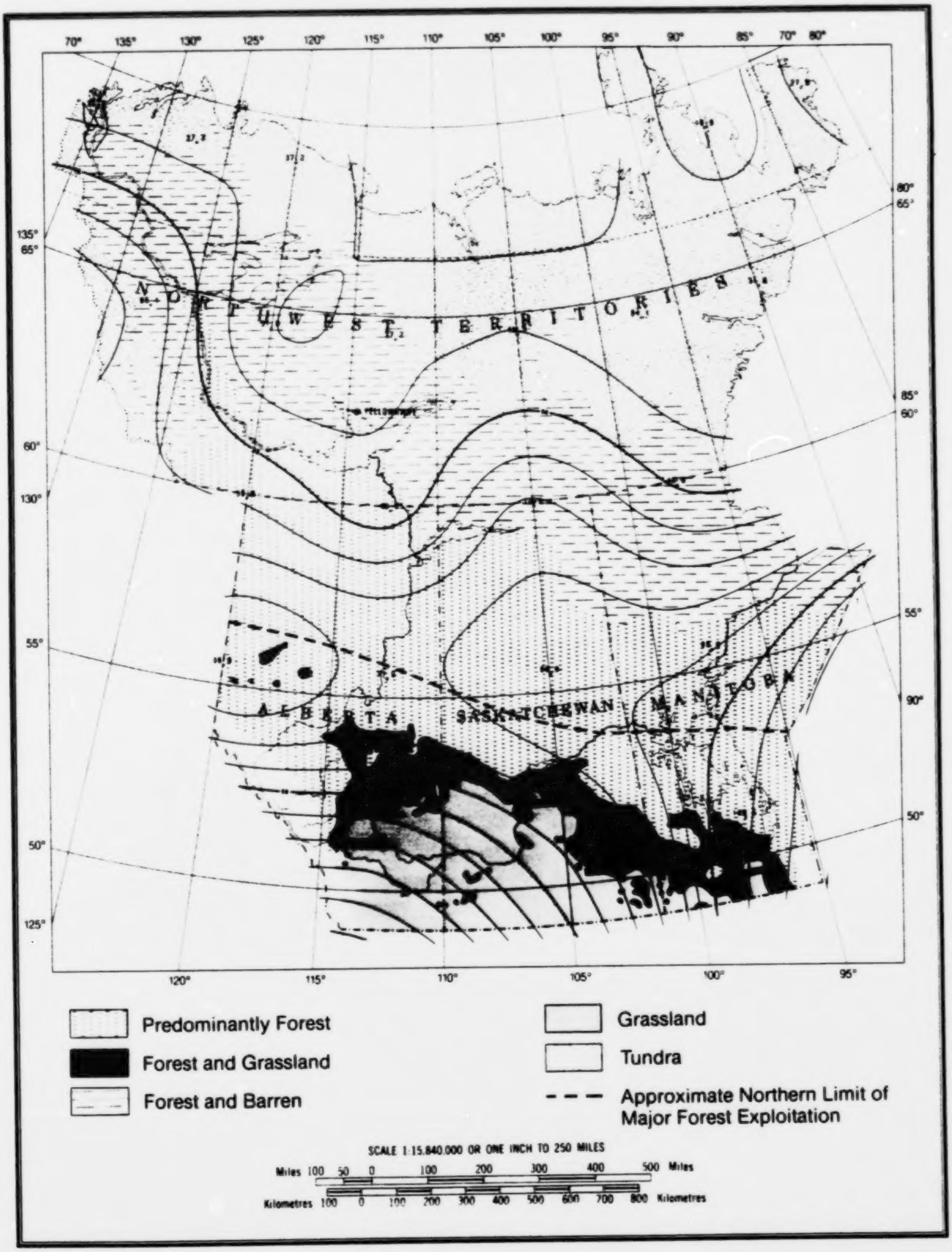
NORTHWEST TERRITORIES
ALBERTA
SASKATCHEWAN
MANITOBA
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres
120° 115° 110° 105° 100° 95°
65° 60° 55° 50°

Figure C.8c Spatial Patterns of Monthly Mean Precipitation Totals for the GFDL1 Climatic Change Scenario for July.

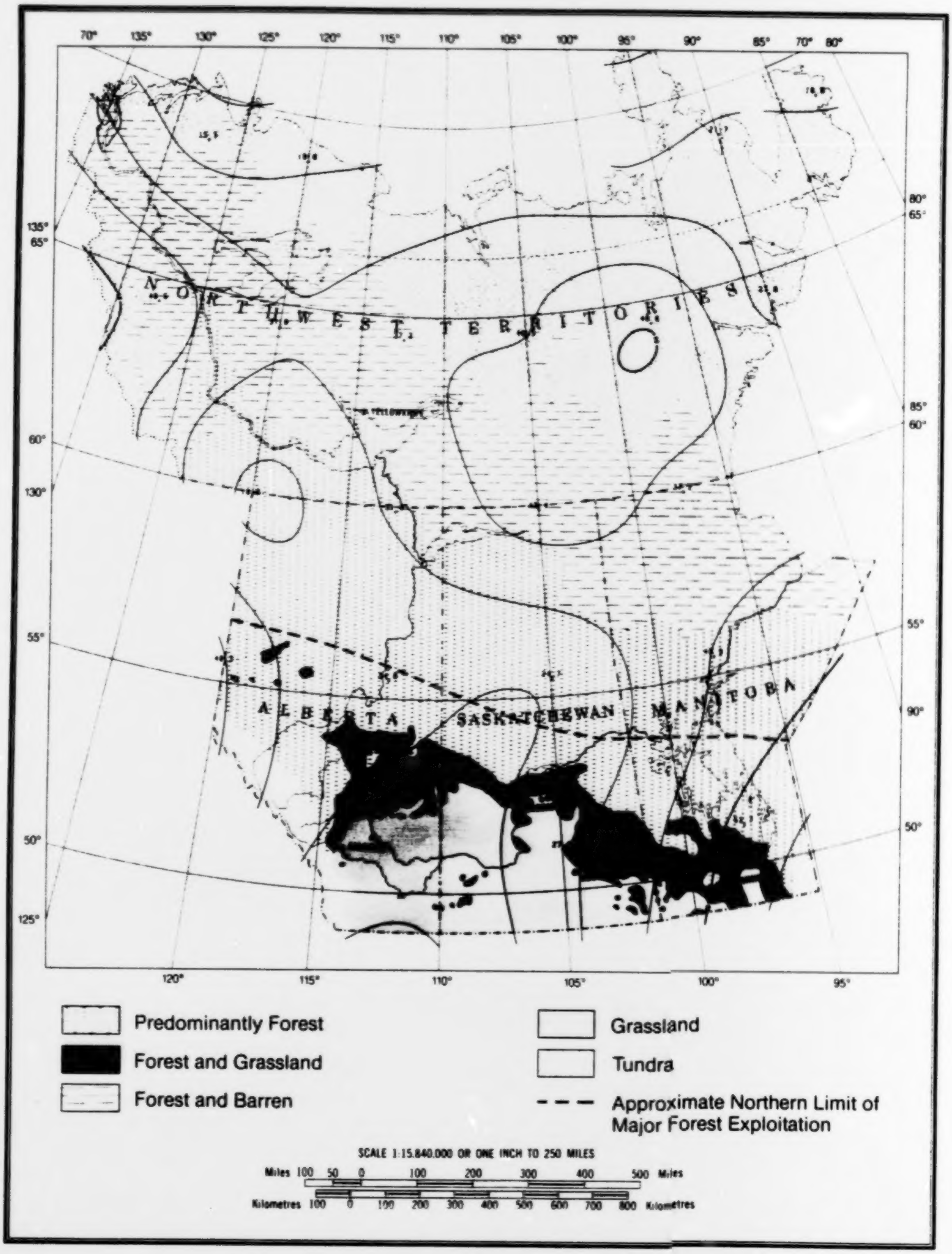
NORTHWEST TERRITORIES
YELLOWKNIFE
ALBERTA
SASKATCHEWAN
MANITOBA
70°
135°
130°
125°
120°
115°
110°
105°
100°
95°
90°
85°
70°
80°
65°
60°
55°
50°
Predominantly Forest
Forest and Grassland
Forest and Barren
Grassland
Tundra
Approximate Northern Limit of Major Forest Exploitation
SCALE 1:15,840,000 OR ONE INCH TO 250 MILES
Miles 100 50 0 100 200 300 400 500 Miles
Kilometres 100 0 100 200 300 400 500 600 700 800 Kilometres

Figure C.8d Spatial Patterns of Monthly Mean Precipitation Totals for the GFDL1 Climatic Change Scenario for October.